# EFFECT OF PROMOTER AND DISTRIBUTOR PARAMETERS ON THE PERFORMANCE OF GAS-SOLID FLUIDIZED BEDS

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*Dedicated to*
*My late parents*

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## CERTIFICATE

This is to certify that the thesis entitled “Effect of Promoter and Distributor Parameters on the Performance of Gas-Solid Fluidized Beds” being submitted by Sri Awadhesh Kumar, Assistant Professor, Department of Applied Mechanics and Hydraulics, National Institute of Technology, Rourkela for the award of Ph.D. degree is a record of bonafide research carried out by him for about four and a half years (1999-2003) under our supervision. In our opinion the work fulfills the requirements for which it is being submitted.

The work incorporated in this thesis has not been submitted earlier, in part or in full, for the award of any other degree or diploma of this or any other University or Institution.

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(Awadhesh Kumar)

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## S Y N O P S I S

The technique of fluidization finds extensive industrial applications for its certain advantages viz. smooth, liquid like flow of particles which enable continuous, automatically-controlled operation with ease of handling, rapid mixing of solids leading to near isothermal condition throughout the bed, high rate of heat and mass transfer. However, in large diameter and deep gas-solid beds, the quality of fluidization is seriously affected by problems of bubbling and slugging which result in excessive height of the fluidizer and makes the operation uneconomical. In addition, channelling in such beds also adversely affect the gas-solid contact. There have been persistent efforts to minimize the above problems by the use of non-cylindrical columns in place of conventional cylindrical ones, imparting vibration to the column, use of improved design for distributor and of promoters with suitable shape and configuration.

A review of literature reveals that some investigations relating to fluidization quality have been carried out in a few cylindrical and non-cylindrical viz. semi-cylindrical, square, conical and hexagonal two-dimensional beds. Although these investigations have thrown some light on the performance of such beds of varied configuration, definite conclusions (qualitative/quantitative) have not been arrived at as regards their improved performance on a comparative basis with respect to a conventional bed. The literature provides limited quantitative study on the effect of promoters on related parameters in gas-solid fluidization viz. bed expansion, fluctuation, and pressure drop, minimum fluidization velocity and bubble behaviour.

Hence the present work has been taken up to quantify the effect of promoters on bed expansion, fluctuation, and pressure drop, minimum fluidization velocity and bubble behaviour in case of gas-solid fluidization through extensive experimentation.

The promoters used are: rod promoters in four different configuration, seven number of disk promoters of varying disk thickness and diameter, and one blade promoter. The effect of distributors was also studied using five number of distributors of varying open area and aperture size. The work undertaken has been presented in eight chapters and four appendices in the thesis.

**Chapter- 1** outlines the introduction to different inherent problems of gas-solid fluidized bed along with their impact on the fluidization phenomenon and the objectives of the investigation undertaken.

**Chapter - 2** presents the literature review which summarizes the up-to-date investigations related to bed dynamics viz. bed expansion, fluctuation, and pressure drop, minimum fluidization velocity, and bubbling behaviour in promoted as well as conventional unpromoted beds. Investigations in gas-solid fluidized beds with promoter of various shape and specification and supported by different types of distributor have also been incorporated in this chapter.

**In chapter - 3**, the experimental setup with details of promoters and distributors used in a cylindrical column along with the experimental procedures adopted for different aspects of investigation have been outlined. Altogether 69 sets of run were taken for gas-solid system with and without promoters. The system variables include bed material of varying particle size, initial static bed height and distributors of varying open area. Four rod promoters of different blockage volume, seven disk promoters of varying disk thickness and diameter, and one blade promoter with blockage volume same as one each of the rod promoters and disk promoters have been used. This chapter also presents data analysis for the development of correlations in dimensionless terms and also for the development of Artificial Neural Network (ANN) models. The scope of the present investigation has been presented in Table-1.

**Chapter -4** deals with the prediction of bed expansion ratio ($R$) i.e. the ratio of the average height of a fluidized bed to initial static bed height at a particular flow rate of the fluidizing medium above the minimum fluidization velocity. Thus, bed expansion ratio is a function of static and dynamic properties of the fluidized bed. The relation can be expressed as functions of dimensionless terms containing bed, distributor and promoter parameters and the properties of the fluidized particles and the fluidizing medium. These correlations have been expressed in the form of modified bed expansion ratio $\left(R'\right)$ in order to ensure boundary condition of zero expansion against zero excess velocity at the onset of fluidization.

The analysis of the experimental data for the effect of the individual dimensionless group has been carried out. Using the values of the constants and the exponents as obtained by the regression analysis of the data, the final correlations for modified bed expansion ratio have been obtained as under:

**Unpromoted bed**

$$R' = 0.37\left(G_R\right)^{0.85}\left(\frac{\rho_s}{\rho_f}\right)^{0.59}\left(\frac{A_{do}}{A_c}\right)^{0.20}\left(\frac{d_p}{d_o}\right)^{0.41}\left(\frac{h_s}{D_c}\right)^{-0.32} \qquad \text{(i)}$$

**Bed with rod promoter**

$$R' = 0.18\left(G_R\right)^{0.74}\left(\frac{\rho_s}{\rho_f}\right)^{0.56}\left(\frac{A_{do}}{A_c}\right)^{0.19}\left(\frac{d_p}{d_o}\right)^{0.29}\left(\frac{h_s}{D_c}\right)^{-0.40}\left(\frac{D_e}{D_c}\right)^{0.23} \qquad \text{(ii)}$$

**Bed with disk promoter**

$$R' = 0.08\left(G_R\right)^{0.75}\left(\frac{\rho_s}{\rho_f}\right)^{0.56}\left(\frac{A_{do}}{A_c}\right)^{0.19}\left(\frac{d_p}{d_o}\right)^{0.26}\left(\frac{h_s}{D_c}\right)^{-0.47}$$

$$\times\left(\frac{t}{D_c}\right)^{-0.24}\left(\frac{D_k}{D_c}\right)^{-0.48} \qquad \text{(iii)}$$

**Bed with blade promoter**

$$R' = 0.24\left(G_R\right)^{0.73}\left(\frac{\rho_s}{\rho_f}\right)^{0.51}\left(\frac{A_{do}}{A_c}\right)^{0.17}\left(\frac{d_p}{d_o}\right)^{0.22}\left(\frac{h_s}{D_c}\right)^{-0.71} \qquad \text{(iv)}$$

The comparison of the predicted results for the bed expansion ratio for the unpromoted and promoted beds indicates that all types of promoters used in the investigation are quite effective in reducing the bed expansion over the unpromoted ones. For identical operating conditions, the beds with disk and blade promoters have been observed to be more effective (with blade promoter being better in performance) in reducing bed expansion when compared with beds having rod promoters. Also, the decrease of the distributor open area results in the reduction of bed expansion. Thus, the combined effect of an appropriate promoter and a distributor with decreased open area results in better quality of gas-solid fluidization with reduced bubble formation and slugging, thereby limiting the size of the bed with appreciable reduction of transport disengaging height (TDH)

This chapter also includes the development of **A**rtificial **N**eural **N**etwork **(ANN)** models based on experimental data, for the prediction of bed expansion ratio and their use to authenticate and support the results obtained using developed correlations. Four such ANN-models have been developed for unpromoted bed and beds with rod, disk and blade promoters. The coefficient of determination $\left(R^2\right)$ for training and testing data in all the cases of unpromoted and promoted beds indicates the proper training of the data for neural network models. The bed expansion ratio predicted from the developed correlations have been found to compare fairly well with the corresponding experimental results and the values predicted by ANN models.

**Chapter-5** presents the prediction of bed fluctuation ratio ($r$) defined as the ratio of the highest and the lowest levels which the top of a fluidized bed occupies for any particular flow rate of the fluidizing medium above the minimum fluidization velocity. For the development of correlation for fluctuation ratio, the modified fluctuation ratio $\left(r'\right)$ has been used in order to ensure zero fluctuation at the onset of fluidization. Four correlations in terms of dimensionless groups for unpromoted bed and promoted beds with rod, disk and blade promoters, have been obtained as under:

**Unpromoted bed**

$$r' = 0.24\left(G_R\right)^{0.85}\left(\frac{\rho_s}{\rho_f}\right)^{0.63}\left(\frac{A_{do}}{A_c}\right)^{0.21}\left(\frac{d_p}{d_o}\right)^{0.41}\left(\frac{h_s}{D_c}\right)^{-0.36} \qquad \text{(v)}$$

**Bed with rod promoter**

$$r' = 0.16\left(G_R\right)^{0.69}\left(\frac{\rho_s}{\rho_f}\right)^{0.50}\left(\frac{A_{do}}{A_c}\right)^{0.13}\left(\frac{d_p}{d_o}\right)^{0.25}\left(\frac{h_s}{D_c}\right)^{-0.38}\left(\frac{D_e}{D_c}\right)^{0.27} \qquad \text{(vi)}$$

**Bed with disk promoter**

$$r' = 0.09\left(G_R\right)^{0.67}\left(\frac{\rho_s}{\rho_f}\right)^{0.46}\left(\frac{A_{do}}{A_c}\right)^{0.14}\left(\frac{d_p}{d_o}\right)^{0.24}\left(\frac{h_s}{D_c}\right)^{-0.46}$$

$$\times\left(\frac{t}{D_c}\right)^{-0.23}\left(\frac{D_k}{D_c}\right)^{-0.67} \qquad \text{(vii)}$$

**Bed with blade promoter**

$$r' = 0.29\left(G_R\right)^{0.51}\left(\frac{\rho_s}{\rho_f}\right)^{0.33}\left(\frac{A_{do}}{A_c}\right)^{0.13}\left(\frac{d_p}{d_o}\right)^{0.18}\left(\frac{h_s}{D_c}\right)^{-0.67} \qquad \text{(viii)}$$

The results have shown that all the promoters used in the study are effective in reducing the bed fluctuation ratio. For identical operating conditions, the bed fluctuation is the least in case of a bed with blade promoter and is maximum in unpromoted bed. The bed with disk promoter has been found to reduce bed fluctuation effectively when compared with bed using rod promoter.

It has further been observed that the decrease of the distributor open area results in the reduction of bed fluctuation. The combined effect of an appropriate promoter and a distributor with decreased open area gives better quality gas-solid fluidization with reduced bubble formation and slugging. This also results in the reduction in the expanded height of the gas-solid fluidized bed thus making the design economical.

In addition to the above analysis, this chapter also deals with the development of four artificial neural network models for the prediction of bed fluctuation and to compare the results predicted from developed correlations. The comparison of the predicted values of bed fluctuation ratio using developed correlations and the ANN models for the respective beds shows close agreement with the corresponding experimental ones.

In **chapter -6**, the development of distributor-to-bed pressure drop ratio for unpromoted as well as promoted beds with rod, disk and blade promoters has been presented. Using different system variables expressed in dimensionless form, the following correlations have been obtained:

**Unpromoted bed**

$$\frac{\Delta p_d}{\Delta p_b} = 1.29\times 10^{-4}\left(G_{mrf}\right)^{1.14}\left(\frac{\rho_s}{\rho_f}\right)^{0.48}\left(\frac{A_{do}}{A_c}\right)^{-1.83}\left(\frac{d_p}{d_o}\right)^{0.89}\left(\frac{h_s}{D_c}\right)^{-1.02} \quad \text{ix)}$$

**Bed with rod promoter**

$$\frac{\Delta p_d}{\Delta p_b} = 8.66\times 10^{-5}\left(G_{mrf}\right)^{1.26}\left(\frac{\rho_s}{\rho_f}\right)^{0.53}\left(\frac{A_{do}}{A_c}\right)^{-2.01}\left(\frac{d_p}{d_o}\right)^{0.94}$$

$$\times\left(\frac{h_s}{D_c}\right)^{-1.18}\left(\frac{D_e}{D_c}\right)^{-0.21} \quad \text{(x)}$$

**Bed with disk promoter**

$$\frac{\Delta p_d}{\Delta p_b} = 9.41\times 10^{-5}\left(G_{mrf}\right)^{1.16}\left(\frac{\rho_s}{\rho_f}\right)^{0.51}\left(\frac{A_{do}}{A_c}\right)^{-1.90}\left(\frac{d_p}{d_o}\right)^{0.93}$$

$$\times\left(\frac{h_s}{D_c}\right)^{-1.06}\left(\frac{t}{D_c}\right)^{-0.12}\left(\frac{D_k}{D_c}\right)^{0.22} \quad \text{(xi)}$$

**Bed with blade promoter**

$$\frac{\Delta p_d}{\Delta p_b} = 1.31\times 10^{-4}\left(G_{mrf}\right)^{1.17}\left(\frac{\rho_s}{\rho_f}\right)^{0.48}\left(\frac{A_{do}}{A_c}\right)^{-1.87}\left(\frac{d_p}{d_o}\right)^{0.92}\left(\frac{h_s}{D_c}\right)^{-1.04} \quad \text{(xii)}$$

The interference of promoters in gas-solid fluidized beds has been observed to increase the distributor-to-bed pressure drop ratio ($\Delta p_d / \Delta p_b$), which means decrease in bed pressure drop for identical flow conditions. In beds with rod promoters, $\Delta p_d / \Delta p_b$ increases with decrease in equivalent diameter of the promoted bed ($D_e$), i.e. with increase in number of vertical rods. In case of beds with disk promoters, $\Delta p_d / \Delta p_b$ values have been found to decrease with increase in disk thickness and decrease in disk diameter. Under similar operating conditions, the presence of disk and blade promoters in the beds has shown marginal increase in distributor-to-bed pressure drop ratio whereas for beds with rod promoters the increase in this pressure drop ratio was significant. Also, the $\Delta p_d / \Delta p_b$ ratio increases with decrease in open area of the distributor resulting in minimum channelling and improved gas-solid fluidization.

The experimental data have also been utilized for the development of ANN based models to predict distributor-to-bed pressure drop ratio ($\Delta p_d / \Delta p_b$) and to support the results predicted by the developed correlations. Four ANN-models using back propagation algorithm, one each for unpromoted bed and beds promoted with rod, disk and blade promoters, have been developed. The predicted values of $\Delta p_d / \Delta p_b$ using developed correlations and that obtained from neural network models have been found to be in good agreement with the corresponding experimental values.

Further in this chapter, formulation of bed pressure drop equation for gas-solid fluidized beds with rod, disk and blade promoters in the line of Ergun and Burke-Plummer has been presented. Using the experimental data, the developed correlation for bed pressure drop is as follows:

$$\Delta p_b = \mathrm{K} L N_{\mathrm{Re}}^{'} \frac{(1-\varepsilon)^2 \mu_f u_f}{\varepsilon^3 \phi_s^2 d_p^2} \tag{xiii}$$

where $\varepsilon = \dfrac{V_e - V_s - V_p}{V_e}$ , $L = R.h_s$

The value of K (constant) has been found to be independent of particle size and density, and initial static bed height. However, for the promoted beds the constant K depends on the type of promoters used in the beds and accordingly different values of K for beds with different promoters have been presented.

A comparison has also been presented between predicted values of bed pressure drop using (i) developed correlations for $\Delta p_d / \Delta p_b$, (ii) modified Burke-Plummer equation and (iii) an equation, $\Delta p_b / L = \left[\rho_s (1-\varepsilon) g\right]$ used for traditional unpromoted gas-solid fluidized bed with the corresponding experimental ones. The values of bed pressure drop calculated with the help of developed correlations for $\Delta p_d / \Delta p_b$ and the modified Burke-Plummer equation have been found to be closer to the experimental values (better agreement found in case of the former) than those obtained from the equation for a traditional fluidized bed.

**Chapter-7** presents the correlations developed for the prediction of minimum fluidization velocity in beds with rod and disk promoters. To show the effect of promoters on minimum fluidization velocity over the unpromoted ones, the promoter parameters have been used in dimensionless form and the following correlations have been developed:

**For bed with rod promoter**

$$G'_{mf} = \left[0.000829 + 0.0001\left(\frac{D_e}{D_c}\right)\right] \times \left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \qquad \textbf{(xiv)}$$

**For bed with disk promoter**

$$G'_{mf} = \left[0.000829 + 3\times10^{-5}\left(\frac{t}{D_c}\right)^{-0.88}\left(\frac{D_k}{D_c}\right)^{2.80}\right]$$

$$\times\left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \qquad \text{(xv)}$$

The average value of the constant (0.000829), has been obtained experimentally in unpromoted fluidized beds with materials of varied size and density. The values of minimum fluidization mass velocity in promoted beds have been found to be higher compared to conventional unpromoted ones. Also, it has been observed that the minimum fluidization mass velocity in a promoted fluidized bed with rod promoter is higher than those with disk promoter for the same blockage volume of the promoter. In case of beds with rod promoters, the minimum fluidization mass velocity increases with increase in the number of rods. For the case of beds with disk promoters, the minimum fluidization mass velocity has been found to increase with decrease in disk thickness and increase in disk diameter. The combined effect of disk thickness and diameter results in a higher value of minimum fluidization mass velocity when compared with a conventional unpromoted bed.

**Chapter-8** outlines the bubbling behaviour with respect to minimum bubbling velocity, bubble diameter, minimum slugging velocity and nature of slug formation in unpromoted as well as promoted beds. The values of the constant ($K_{mb}$)

in equation (xvi) given below for minimum bubbling velocity, as suggested by Geldart have been presented for unpromoted bed and beds with rod, disk and blade promoters.

$$U_{mb} = K_{mb} \overline{d}_s \qquad \text{(xvi)}$$

where $\overline{d}_s = \dfrac{1}{\sum_i \left( \dfrac{X_i}{d_{si}} \right)}$

For the same particle size, the minimum bubbling velocity has been observed to be least in case of unpromoted bed and highest in the case of bed with blade promoter. Under similar operating conditions and with equal blockage volume of the rod, disk and blade promoters, the bubble diameter has been found to be maximum in case of unpromoted bed and minimum in case of the bed with blade promoter. Also, in case of unpromoted bed, slug formation has been observed at comparatively lower velocity than in promoted beds. Among promoted ones, the bed with blade type promoter gives the maximum value with respect to the minimum slugging velocity.

**Appendix-1** presents the values of terminal velocity for four bed materials of the same size as well as five particle sizes of the same material.

**Appendix-2** details the experimental data in the range of investigations which includes 69 sets.

**Appendix-3** includes the list of publications relating to the present and related work by the investigator.

**Appendix-4** contains reprints of the papers published based on the present work.

**Nomenclature**

| | |
|---|---|
| $\overline{d}_s$ | mean surface diameter, L |
| $A_c$ | cross sectional area of column, $L^2$ |
| $A_{do}$ | open area of distributor, $L^2$ |
| $A_o$ | open area in promoted bed with rod promoter, $L^2$ |
| $D_c$ | column diameter, L |
| $D_e$ | equivalent diameter of promoter, $4A_o/P$, L |
| $D_k$ | disk diameter, L |
| $d_o$ | orifice diameter, L |
| $d_p$ | particle size, L |
| g | acceleration due to gravity, $LT^{-2}$ |
| $G_f$ | fluidization mass velocity, $ML^{-2}T^{-1}$ |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted beds, $ML^{-2}T^{-1}$ |
| $G_{mf}^{'}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $G_{mrf}$ | reduced fluidization mass velocity for unpromoted beds, $G_f / G_{mf}$ |
| | reduced fluidization mass velocity for promoted beds, $G_f / G_{mf}^{'}$ |
| $G_R$ | mass velocity ratio for unpromoted beds, $\left(G_f - G_{mf}\right)/\left(G_t - G_{mf}\right)$ |
| | mass velocity ratio for promoted beds, $\left(G_f - G_{mf}^{'}\right)/\left(G_t - G_{mf}^{'}\right)$ |
| $G_t$ | terminal mass velocity, $ML^{-2}T^{-1}$ |
| $h_{av}$ | average height of fluidized bed, L |

| | |
|---|---|
| $h_{\max}$ | maximum height of fluidized bed, L |
| $h_{\min}$ | minimum height of fluidized bed, L |
| $h_s$ | initial static bed height, L |
| $G_t$ | terminal mass velocity, $ML^{-2}T^{-1}$ |
| $K_{mb}$ | constant at minimum bubbling |
| $L$ | expanded bed height, $(h_{\max} + h_{\min})/2$, L |
| $N'_{\mathrm{Re}}$ | modified Reynolds number, $\rho_f u_f \phi_s d_p / (1-\varepsilon)\mu_f$ |
| $P$ | total rod perimeter, L |
| $R$ | bed expansion ratio, $h_{av} / h_s$ |
| $R'$ | modified bed expansion ratio, $R - 1$ |
| $R^2$ | coefficient of determination |
| $r$ | bed fluctuation ratio, $h_{\max} / h_{\min}$ |
| $r'$ | modified bed fluctuation ratio, $r - 1$ |
| $t$ | disk thickness, L |
| $u_f$ | superficial fluid velocity, $LT^{-1}$ |
| $V_e$ | volume of the expanded bed, $L^3$ |
| $V_p$ | volume of promoter, $L^3$ |
| $V_s$ | volume of solid, $L^3$ |
| $X_i$ | weight fraction of particle of diameter $d_s$, L |

***Greek letters***

| | |
|---|---|
| $\varepsilon$ | porosity |
| $\phi_s$ | sphericity |
| $\Delta p_b$ | bed pressure drop, $ML^{-1}T^{-2}$ |
| $\Delta p_d$ | distributor pressure drop, $ML^{-1}T^{-2}$ |
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |
| $\mu_f$ | viscosity of fluid, $ML^{-1}T^{-1}$ |

Table 1 **Scope of the experiment**

| A. Properties of bed material | | |
|---|---|---|
| Materials | $d_p x10^3$,m | $\rho_s x10^{-3}$,kg/m$^3$ |
| Dolomite | 1.125 | 2.817 |
| Dolomite | 0.725 | 2.817 |
| Dolomite | 0.463 | 2.817 |
| Dolomite | 0.390 | 2.817 |
| Dolomite | 0.328 | 2.817 |
| Alum | 0.725 | 1.691 |
| Iron-ore | 0.725 | 3.895 |
| Mangnese-ore | 0.725 | 4.880 |

| B. Bed parameter | | | | |
|---|---|---|---|---|
| Initial static bed height, $h_s$ x $10^2$, m | 8 | 12 | 16 | 20 |

| C. Distributor parameters | | |
|---|---|---|
| Distributor | Number of orifice | Diameter of orifice,$d_o$ , mm |
| $D_1$ | 37 | 1.00 |
| $D_2$ | 37 | 1.50 |
| $D_3$ | 37 | 2.00 |
| $D_4$ | 37 | 2.50 |
| $D_5$ | 37 | 3.00 |

| D. Promoter details | | | | |
|---|---|---|---|---|
| Promoter specification | | $D_k$ x$10^3$ , m | t x $10^3$ , m | No. of 4 mm dia. longitudinal rods |
| Rod : | $P_1$ | — | — | 4 |
| | $P_2$ | — | — | 8 |
| | $P_3$ | — | — | 12 |
| | $P_4$ | — | — | 16 |
| Disk: | $P_5$ | 28.000 | 3.18 | — |
| | $P_6$ | 28.000 | 6.36 | — |
| | $P_7$ | 28.000 | 9.54 | — |
| | $P_8$ | 28.000 | 12.72 | — |
| | $P_9$ | 20.260 | 6.36 | — |
| | $P_{10}$ | 34.000 | 6.36 | — |
| | $P_{11}$ | 39.125 | 6.36 | — |
| Blade: | $P_{12}$ | 38.000 | 6.36 | — |

# CHAPTER I

## Introduction

Gas-solid fluidized beds have found more industrial applications compared to fixed beds due to low pressure drop and good solid-fluid mixing. Some of the important applications of gas-solid fluidized beds are in the dairy, cement industries, food and pharmaceutical industries for drying, cooling, coating and agglomeration. The important advantages of the gas-solid fluidized beds are smooth, liquid-like flow of solid particles. This permits a continuous automatically-controlled operation with ease of handling and rapid mixing of solids leading to near isothermal conditions throughout the bed. This results in a simple and controlled operation with rapid heat and mass transfer rates between gas and particles, thereby minimizing overheating in case of heat sensitive products.

Albeit the above-mentioned advantages of gas-solid fluidized beds, the efficiency and the quality in large diameter and deep beds suffer seriously due to certain inherent drawbacks such as channelling, bubbling and slugging. These result in poor homogeneity of the fluid and ultimately affect the quality of fluidization. The formation of bubbles and their ultimate growth to form slugs and the collapsing of bubbles cause erratic bed expansion with intense bed fluctuation. The excessive bed expansion and fluctuation result in increased Transport Disengaging Height (TDH) of the fluidizer and hence becomes uneconomical from the point of view of system design. Formation of large scale bubbles also reduce the heat and mass transfer rate which affect the output of the system. Hence persistent efforts have been made by the investigators to improve the quality of gas-solid fluidization by promoting bubble breakage and hindering the coalescence of bubbles which result in reduced bed expansion and fluctuation and better gas-solid mixing.

A glance into the literature reveals that some investigations relating to fluidization quality have been carried out in a few cylindrical and non-cylindrical viz. semi-cylindrical, square, conical and hexagonal two-dimensional unpromoted beds. Although these investigations have been able to throw some light on the performance of such beds of non-conventional configurations, definite conclusions (qualitative/quantitative) have not been arrived at as regards their improved performance on a comparative basis with respect to a conventional bed.

To overcome the above-mentioned drawbacks of gas-solid fluidized beds and to improve fluidization quality, several techniques such as vibration and rotation of the bed, use of improved distributor and turbulence promoter, application of conical and non-cylindrical conduits in place of the columnar ones have been recommended by the investigators. Out of the various a-fore-said techniques suggested, the use of suitable promoters have been found to be more effective in controlling fluidization quality as compared to other methods. The inclusion of a promoter in the gas-solid fluidized bed has been found to be effective in breaking up of the bubbles, controlling their size and growth leading to more frequent and smaller bubbles of uniform size and distribution within the bed without imposing any extra operational cost. These improvements in fluidized bed are related to fluidization parameters viz. minimum fluidizing mass velocity and bed expansion, fluctuation and pressure drop. A number of investigators have recommended the use of a suitable promoter in order to achieve improved fluidization quality with nominal additional fabrication expenditure and no extra operational cost.

The use of a properly designed gas distributor can also improve fluidization quality by minimizing slugging and reducing the size of bubbles and their growth. An improved gas distributor distributes the fluidizing gas across the base of the bed so that uniform flow is maintained in the fluidized condition over the whole of its cross section. This results in ultimate reduction of bed expansion and fluctuation to a considerable extent.

A literature review on the performance of promoted gas-solid fluidized beds with respect to bed pressure drop, minimum fluidizing mass velocity and other fluidization related parameters specially in terms of bed expansion and fluctuation, provide little information. Most of the available literature explain qualitatively some effect of turbulence promoters on the parameters effecting the quality of fluidization.

In the present case, an extensive experimentation has been conducted to study the combined effect of promoter and distributor parameters on bed dynamics relating to minimum fluidization velocity, bed pressure drop, bed expansion and fluctuation. A total of three different types of promoters viz. rod type (four number of varying rod configuration and blockage), disk type (eleven number of varying disk thickness and diameter) and one blade type have been used in the investigation. Other system variables include gas distributor (five number of different opening area), bed materials of different size and density and initial static bed height.

# CHAPTER II
# Review of literature

## 2.1 Introduction

Fluidization is an established fluid-solid contacting technique. A fluidized bed can be achieved by increasing the upward velocity of the fluid through a fixed bed of solid particles. Fluidized bed technique as compared to fixed bed has the unique advantage of a smooth, liquidlike flow of solid particles which allows continuous and automatically-controlled operation with ease of handling and rapid mixing of solids. This leads to near isothermal conditions throughout the bed providing rapid heat and mass transfer rates between fluid and solid particles, thereby minimizing overheating in case of heat sensitive products.

In spite of the above-mentioned advantage, the applications of gas-solid fluidized bed have been constrained due to certain inherent drawbacks like channelling, uncontrolled bed expansion and fluctuation because of formation of bubbles and their subsequent collapsing, and slugging. These not only reduce the transfer rate thereby affecting the outcome of the system, but influence the fluidization quality to a considerable extent.

Some remedial measures proposed for the a-fore-said problems with a view to improving the quality of fluidization include the incorporation of turbulence promoters (baffles/internals/inserts) in the bed, imparting vibration and rotation to the bed, operation in a multistage unit and the use of conical and other non-cylindrical conduits in place of the conventional columnar ones. The use of a proper gas distributor is also a proposition for the improvement of fluidization quality in gas-solid fluidized beds.

### 2.1.1 Turbulence promoter

Out of the above-mentioned techniques to improve the quality of fluidization, the use of a suitable promoter has been found to be more effective in controlling fluidization quality as compared to other methods. The introduction of a turbulence promoter in a gas-solid fluidized bed enhances the fluidization quality by minimizing bubbling, channelling and slugging. The specific effect of a promoter is realised in controlling the bubble behaviour viz. hindering the formation and growth of bubbles, limiting their size and thereby reducing the bed expansion and fluctuation. To improve the quality of fluidiztion and to increase the range of applicability of gas fluidized beds, Glass and Harrison [1], Zabrodsky [2], Grace and Harrison [3], Davidson and Harrison [4], Wadhera and Sharma [5], Jin et al. [6, 7], Coronella et al. [8], Jiang et al. [9], Duursma et al. [10] and Kumar and Roy [11] have stressed on the use of promoters.

### 2.1.2 Distributors

The major function of a distributor is to distribute the fluidizing gas across the base of the bed so that uniform flow is maintained in the fluidized condition over the whole of its cross section apart from supporting the weight of the defluidizing bed and preventing the flow back of particles during downtime. The improper design/selection of distributor does not fluidize the whole of the cross section of the bed on start up or during the course of operation and a part of the bed defluidizes, blocking thereby a portion of the discharge area. On the basis of advantages and disadvantages of different air distributors viz. perforated plate, gill plates (punched hole plates), flex plates (variation of the gill plate), and non-sifting flex plate (variation of the flex plate), Masters [12] explained that in spite of much development in plate design, the perforated plate is still in use as standard fluidized bed distributor plate due to limited available literature on the other types of distributor plate. From the experimental result on particle mixing and segregation in a gas-solid fluidized bed, Wang and Huang [13] observed that the perforated plate with low open area or less holes perform better.

A brief literature survey on various fluidized bed characteristics relating to the quality of fluidization in unpromoted and promoted fluidized beds with different types of promoter has been presented. This also includes the bed dynamics of fluidized bed supported by distributors of various specifications.

## 2.2 Bed dynamics

Investigations in the field of dynamic studies relating to various aspects of gas-solid fluidization have been carried out by many investigators. Claus et al. [14] studied the hydrodynamics of gas-solid flow through a open ended screen cylinders packed with a voidage of 0.972. Different authors have studied the various aspects of screen packed fluidization viz. limitation of bubble size by Ishii and Osberg [15] and Kang and Osberg [16], the disappearance of slugging by Sutherland et.al. [17], the existence of homogeneous (pseudo particulate) fluidization by Chen and Osberg [18], Kang et al. [19], Capes and Mcllhinney [20] and Park et al. [21, 22], the limitation of gas axial mixing by Chen and Osberg [18] and retention of internal thermal conductivity by Jair and Chen [23]. Claus et al. (loc. cit.) observed that a unique relationship between the relative velocity and the bed voidage does not exist. They explained that the reason for the non-existence of this relationship could be the fact that friction forces between packing and particles greatly contribute to the balance of forces for continuous countercurrent as well as for batch system.

The important work on bed dynamics viz. bubbling, channelling, slugging, minimum fluidization velocity, bed pressure drop, bed expansion, and bed fluctuation responsible for the quality of fluidization in unpromoted as well as promoted beds have been discussed and explained herein as under:

### 2.2.1 Bubbling

A gas-solid fluidized bed is characterized by the presence of gas voids or bubbles causing a resistance to mass and heat transfer. Bubbles in gas fluidized bed are very important as they are responsible for most of the features that differentiate a packed bed from a fluidized one. The quality of fluidization specially in terms of expansion and fluctuation depends largely on the formation of bubbles and their growth in the direction of flow. Modification of gas flow promotes the formation of bubbles of smaller size through the system and cause particle movement which generally results reduced expansion and fluctuation, rapid and extensive particle mixing and a consequent high heat transfer co-efficient.

Wilhelm and Kwauk [24] proposed the use of Froude number $\left(Fr_{mf}\right)$ as a criterion for bubbling or aggregative fluidization. A value of $Fr_{mf} > 1.0$ induces a bubbling behaviour in the bed, where,

$$Fr_{mf} = \frac{U_{mf}^2}{d_p g} \tag{2.1}$$

Romero and Johanson [25] extended this idea to four dimensionless groups of relevance which include the Reynolds number $\left(\frac{d_p U_{mf} \rho_f}{\mu_f}\right)$ and the Froude number. Accordingly the criterion for bubbling or aggregative fluidization is,

$$\left(Fr_{mf}\right)\left(R_{ep,mf}\right)\left(\frac{\rho_s - \rho_f}{\rho_f}\right)\left(\frac{h_{mf}}{d_b}\right) \rangle 100 \tag{2.2}$$

A correlation for minimum bubbling velocity was suggested by Geldart [26] as

$$U_{mb} = K_{mb} \overline{d_s} \tag{2.3}$$

where $$\overline{d_s} = \frac{1}{\sum_i \left(\frac{X_i}{d_{si}}\right)} \tag{2.4}$$

and $K_{mb}$ = Constant whose value is 100 in C. G. S. unit.

Abrahamsen and Geldart [27] observed that the addition of fines in a bed of small particles improves the quality of fluidization by increasing the minimum bubbling velocity and the extent of particulate expansion. They proposed the following correlation:

$$U_{mb} = 2.07\left[\exp\left(0.716X_f\right)\frac{\overline{d_s}\rho_f^{0.06}}{\mu_f^{0.347}}\right] \tag{2.5}$$

Combining minimum bubbling velocity equation with Baeyens and Geldart's [28] equation for minimum fluidizing velocity, Abrahamsen and Geldart (loc. cit.) determined the ratio-

$$\frac{U_{mb}}{U_{mf}} = \frac{2300\rho_f^{0.126}\mu_f^{0.523}\exp\left(0.716X_f\right)}{\left(\overline{d}_s\right)^{0.8}g^{0.934}\left(\rho_s-\rho_f\right)^{0.934}} \tag{2.6}$$

showing that $\frac{U_{mb}}{U_{mf}}$ increases with the amount of fines.

Godard and Richardson [29] have shown that the velocities of individual bubbles in freely bubbling beds are influenced more markedly by the disposition of surrounding bubbles than by the size of the individual bubble itself. Bubbles present in high concentration rise at much greater velocities than isolated bubbles of the same volume.

Bubble size in a gas-solid fluidized bed (when size is not restricted by the column dimension) can be predicted by a correlation proposed by Rowe [30] as

$$d_b = \frac{\left(U_f - U_{mf}\right)^{1/2}\left(h+h_o\right)^{3/4}}{g^{1/4}} \tag{2.7}$$

Darton et al. [31] have suggested another correlation for bubble size-

$$d_b = \frac{0.54\left(U_f - U_{mf}\right)^{0.4}\left(h+\sqrt{\frac{A}{n}}\right)^{0.8}}{g^{0.2}} \tag{2.8}$$

Mori and Wen [32] have shown the effect of height from distributor plate on bubble size as-

$$\frac{d_{bm}-d_b}{d_{bm}-d_{bo}} = \exp\left(\frac{-0.3h}{D_c}\right) \tag{2.9}$$

From the studies on the break-up of a large single gas bubble in liquid and/or liquid-solid fluidized beds, Clift and Grace [33] observed that the inherent bubble splitting in the absence of constant external disturbances is due to Rayleigh-Taylor instability along the bubble frontal surface. When such disturbances are present, the bubble is more easily disintegrated. For instance, shear stresses present in the liquid flow can break the bubble long before the instability grows. In three phase-fluidized beds, it has been observed that large, heavy particle will penetrate through the bubble and often result in bubble breakage. The mechanism of bubble break-up caused by these external disturbances is quite different from that caused by Rayleigh-Taylor instability. Under strong bubble-bubble interactions, the mechanism due to external disturbances is considered to predominate.

Rowe et al. [34] reported that X-ray pictures of bubbles in fluidized beds show a systematic change of shape with size. Relatively undisturbed bubbles are spherical but contain a particle wake that cuts off the lower part of the sphere. With increasing size, the wake becomes proportionately greater so that larger bubbles appear flatter than smaller ones. It was proposed that volume varies as diameter raised to power 2.5

Williams [35] concluded that baffles (promoters) within a fluidized bed lead to more frequent and smaller bubbles, of a more uniform size and distribution within the bed. He also found that extensive baffling is not necessary for good gas-solid contact.

The ability of pagoda shaped internal to break up bubbles and enhance gas-solid contact have been demonstrated by Jin et al. [6, 7] using still and movie photographs. Jin et al. [6] concluded that the pagoda type baffle (promoter) combines the advantages of both horizontal and vertical baffle while remedying their defects to some extent, thus affording an opportunity to improve appreciably the performance of fluidized bed reactor. Jin et al. [7] observed substantial improvement in the breaking up of the bubbles and the circulation of solid particle in the bed especially for high gas velocity.

The effect of promoter consisting of 3 mm thick perforated PVC plates with and without downcomer on the fluidization characteristics, particularly on bubbling was investigated in the integrated fluid bed unit system by Kono and Jinnai [36]. Due to the existence of the dilute phase between each unit bed, the promoter worked as a kind of gas distributor. They reported that the bubble sizes can be kept significantly smaller than those in the conventional beds and maintained almost constant regardless of the bed height. The use of promoters like fixed packing, horizontal or vertical promoters would arrest bubble growth and redistribute the gas and improve the homogeneity of the fluidized bed.

Xiaogang et al. [37] observed the effect of operating conditions on bubble behaviour in a fluidized bed with perforated baffles (promoters) and concluded that for the same superficial gas velocity, bubble frequency and rise velocity are independent of aperture ratio, hole diameter (baffle plate) and baffle plate distance.

Dutta and Suciu [38] studied qualitatively the effectiveness of baffles (promoters) in breaking up of bubbles using a total number of 29 baffles of various patterns such as (i) perforated plate, (ii) wire mesh, (iii) angle iron grid, (iv) two-layer angle iron grid, (v) slotted grid made of parallel plates, (vi) slotted grid made of parallel tubes, (vii) simulated in-bed cooling coils, (viii) two-layers louvres, (ix) egg crate, (x) pyramid grid of concentric cylinders, and (xi) vertical open-tube bundle. They concluded that the effectiveness of a flat or a nearly-flat surface baffle, such as a perforated plate, wire mesh or parallel flat plate baffle, may be directly correlated with the percent open area and the number of openings per unit cross section of the baffle. For baffles of other geometries, the details of each baffle type together with the proper definition of an 'effective' open area for each geometry would be required for developing guidelines for commercial baffle design.

Duursma et al. [10] presented novel observation of the two-dimensional obstacle-induced voids in marginally fluidized beds. They observed cinematographically the evolution of obstacle-induced voids and found that void formation was periodic and symmetric about the vertical axis, but asymmetric void formation was also apparent when bubble initiated from the distributor interfered with the flow around the tube (obstacle).

Olowson [39] carried out experimental investigation to study the influence of pressure and fluidization velocity on the hydrodynamics of a fluidized bed containing horizontal- tubes configuration and reported that the influence of pressure and fluidization velocity was basically the same as in the bed without tubes. An increase in pressure and fluidization velocity increases the bubble activity. At low excess gas velocities, the influence of immersed tubes on the bubble behaviour is less pronounced than at high excess gas velocities. Measurement and visual observation indicated that a small tube pitch gives a more uniform distribution of the visible bubble flow over the bed cross-section. At a combination of high pressure, high excess gas velocity and a large tube pitch, a preferred bubble path was observed in the centre of the bed cross-section. Also, the through-flow velocity of gas inside the bubbles is in most cases higher when tubes were present in the bed and consistently decreases with increasing pressure in the bed without tubes.

Further Papa and Zenz [40] have suggested that the use of promoters is one possible way to cause break-up of the bubbles thereby reducing the bubble size.

Feng et al. [41] carried out experiments to study the effect of distributor design on hydrodynamic behaviour of fluidized bed using four distributors of varying configuration. Using motion pictures to study bubble formation and coalescence and tracer particles to study mixing patterns, they concluded that

a) The distributor with two-size orifices causes non-uniform gas bubble flow in the bed. This non-uniform gas flow changes the local density (local voidage) of the fluidized bed and thereby the local resistance inside the bed is varied. Horizontal solid circulation also is caused by this non-uniform gas bubble flow.
b) The variation in local resistance and solid circulation causes bubbles to move towards the region above the small orifices as bubbles rise and coalesce.
c) A two-size orifice plate with small orifices in the centre results in more uniform fluidization and better mixing. Hence, the bubble movement inside the bed can be controlled by changing the distributor configuration.

### 2.2.2 Slugging

The gas-solid fluidization is characterized by the formation of bubble. The size of the bubble increases and sometimes even its diameter may become equal to that of the column. When the bubble diameter approaches the column diameter, it is termed as slugging. An aggregatively fluidized bed in a column of small diameter operated at sufficiently high gas velocity will show continuous slug flow. Slugging affects adversely the fluidization quality. Once slugging occurs, the portion of the bed above the bubble is pushed upwards, as by a piston. Particle rain down from the slug and the slug finally disintegrates. Periodically another slug forms and thus unstable oscillatory motion is repeated. Slugging increases the problem of entrainment and lowers the performance potential of the bed. Slugging is especially serious in long narrow fluidized beds.

Bubble size and its rise velocity are important fundamental properties of gas-fluidized beds. It is also important to know whether or not the bubbles may grow big enough to cause slugging. In gas-liquid or gas-liquid-solid contacting devices, Tsuchiya et al. [42] explained that the bubble coalescence and break-up play a crucial role in determining the distribution of bubble size, its rise velocity and gas-liquid interfacial area in case of a two-dimensional liquid-solid fluidized bed with a stream of bubbles.

Bubbles formed at the distributor, coalesce in the normal way until they reach the size of a slug. Stewart and Davidson [43] stated that at superficial gas velocity below the following bubble rise velocity, slugging should not take place:

$$U_{ms} = U_{mf} + 0.07\sqrt{gD_c} \tag{2.10}$$

The bed must be sufficiently deep for coalescing bubbles to attain the size of a slug. Baeyens and Geldart [44] concluded that the above condition is applicable only if $h_{mf} > 1.3D_c^{0.175}$ in SI units, otherwise the minimum slugging condition is given by-

$$U_{ms} = U_{mf} + 0.07\sqrt{gD_c} + 0.16\left(1.3D_c^{0.175} - h_{mf}\right)^2 \tag{2.11}$$

Bubble coalescence in liquid has been studied both experimentally and theoretically for two successive bubbles in a chain of bubbles by De Nevers and Wu [45] and in a swarm of bubbles by Otake et al. [46]. Korte et al. [47] reported that the bubble coalescence can be reduced by injecting bubbles in certain pattern, which leads to a reduction of the average bubble size higher in the bed.

Matsen et al. [48] gave slug rise velocity as below:

$$U_s = U_{s\infty} + U_f - U_{mf} \tag{2.12}$$

The slugging in the upper part of the bed increases the velocity above the value given by Eq. 2.12. Particularly for coarse particles, the mean total pressure drop across a slugging bed may continue to increase with gas velocity for $U_f > U_{mf}$

Coronella et al. [10] reported a method to determine the gas velocity corresponding to the transition from the bubbling to slugging regime in a fluidized bed containing vertical rods. Measurement of pressure-drop has been used to characterize the regime of fluidization. The dominant frequency $\left(f_d\right)$ in the power spectrum density function (PSDF) of the pressure fluctuation is constant in the slugging regime. Therefore the proposed criterion for slugging is that $f_d$ be constant over a range of fluidizing gas velocities. They concluded that $U_{ms}$ is increased or in other words slugging is suppressed in baffled (promoted) bed with vertical rods.

### 2.2.3 Channelling

The quality of fluidization specially in term of mixing is greatly affected by channelling. As the flow rate through a bed of particle increases towards minimum fluidization of the bed materials, channelling may occur. The non-uniformity in size of bed materials and poor mixing between the fluid and the particles in the bed may lead to channelling. At the onset of the formation of channelling, the fluid tends to pass through the bed along such paths of lower particle concentration. Channelling can result from initial non-uniformity in the bed and tends to be accentuated by stickiness of the particle which prevents them from flowing into the channelled region. Handley et al. [49] and Couderc and Angelino [50] have demonstrated that channelling is linked to a mal-distribution of the fluid at the base of the bed. Where the fluid velocity is significant, the solid particles develop an upward movement, while in case of lower fluid velocity they go downwards. The local increase in velocity through the bed above minimum fluidization, causes the bed to locally expand, thereby altering the pressure drop through that portion of the bed. The change in local pressure drop through the distributor and the combined pressure drop of the bed and the distributor quantify the channelling. A channel tends to become established if the local pressure drop through the bed-distributor system decreases with increased fluid velocity.

Williams [35] concluded that extensive use of promoters in the bed is not necessarily good for gas-solid contact. Balakrishnan and Rao [51] concluded that the use of horizontal screen disk, radiating screen and concentric screen cylinder as promoters cause negligible channelling.

Siegel [52] studied the effect of distributor plate-to-bed resistance ratio at the onset of fluidized bed channelling. He explained that the tendency to channel depends on stability consideration. The stability depends on the combined pressure drop across the bed and the distributor. In case the pressure drop across the combined bed and distributor increases with an increase in local velocity, then the channel formation will tend to be damped out. Siegel (loc. cit.) suggested that for a wide range of Galelio number (1-$10^4$), the minimum ratio of distributor-to-bed resistance required for stability is between 0.14 and 0.22.

The stability of a bed distributor system was also considered by Hiby [53] who indicated that for a porous distributor plate and condition near minimum fluidization, the pressure drop through the distributor should be atleast 30% of that through the bed to provide uniform fluidization. Agarwal et al. [54] recommended a pressure drop across the distributor of 10% of the bed pressure drop when the bed is deep or of high density materials. In case of shallow depth of low density materials, the pressure drop through the distributor should not fall below 3.45 kN/$m^2$. Sathiyamoorthy and Rao [55] concluded that the choice of the distributor-to-bed pressure drop ratio ($\Delta p_d / \Delta p_b$) for stable operation of a fluidized bed depends on the $U_M / U_{mf}$ ratio and developed expression to determine $U_M$ as under:

$$\frac{U_M}{U_{mf}} = 2.65 + 1.24 \log_{10}\left(\frac{U_t}{U_{mf}}\right) \tag{2.13}$$

From the available literature on gas distributors for gas fluidized beds, Qureshi and Creasy [56] proposed the following equation relating the critical value of the distributor-to-bed pressure drop ratio to the aspect ratio of the bed for stable operation:

$$R_c = 0.01 + 0.2\left[1 - \exp\left(-0.5\frac{D_c}{h_s}\right)\right] \tag{2.14}$$

### 2.2.4 Minimum fluidization velocity

When a fluid passes upwards through the interstices of a bed of solids without the slightest disturbance of the solids, the bed is called a fixed bed. With further increase in the velocity of fluid, the entire bed of solids is suspended and behaves as if its weight is counterbalanced by the force of buoyancy. At this point, the bed of solids starts behaving like a fluid. This is called onset of fluidization and the velocity of fluid at which it happens, is called minimum fluidization velocity, which is one of the most important parameter for the design of fluidizers.

At the onset of fluidization, drag force due to upward flow is balanced by the weight of the bed particles which can be mathematically represented as:

$$\left(\Delta p_b\right)A_c = \left(A_c.h_{mf}\right)\left(1-\varepsilon_{mf}\right)\left(\rho_s-\rho_f\right)g \tag{2.15}$$

There are several correlations proposed by Leva [57], Rowe and Henwood [58], Narsimhan [59], Wen and Yu [60], Richardson [61], etc., out of which Ergun's correlation [62] being used over a wide range of Reynolds number is given below:

$$\frac{\Delta p_b}{h_s} = 150\frac{\left(1-\varepsilon_{mf}\right)^2 \mu_f U_{mf}}{\varepsilon_{mf}^3\left(\phi_s d_p\right)^2} + 1.75\frac{\left(1-\varepsilon_{mf}\right)\rho_f U_{mf}^2}{\varepsilon_{mf}^3 \phi_s d_p} \tag{2.16}$$

The superficial velocity at minimum fluidizing conditions, $U_{mf}$ is found by combining Eqs. 2.15 and 2.16 as

$$\frac{1.75}{\phi_s \varepsilon_{mf}^3}\left(\frac{d_p U_{mf}\rho_f}{\mu_f}\right)^2 + \frac{150\left(1-\varepsilon_{mf}\right)}{\phi_s^2\varepsilon_{mf}^3}\left(\frac{d_p U_{mf}\rho_f}{\mu_f}\right) = \frac{d_p^3\rho_f\left(\rho_s-\rho_f\right)g}{\mu_f^2} \tag{2.17}$$

Kawabata et al. [63] have measured the bed pressure drop as a function of superficial gas velocity under pressure in two-dimensional bed. It is indicated that both the pressure drop of the fixed bed and the rate of its change increase with pressure, resulting in a decrease in the minimum fluidization velocity. It is further mentioned that the change in minimum fluidization velocity is greater for coarser particles and that the rate of change decreases as the pressure becomes higher. A correlation was given for $U_{mf}$ as

$$U_{mf} = \frac{10^{-3}}{P}\left(\frac{\mu_f}{\rho_f}\right)\sqrt{33.7^2 + 0.408\left(\frac{\rho_s g \rho_f d_p^3}{\mu_f^2}\right)}P^{-0.337} \tag{2.18}$$

Balakrishnan and Rao [51] conducted investigations to choose the right type of geometry of wire mash screen baffles (promoters) among (i) radiating screen baffles, (ii) concentric screen cylinder baffles and (iii) horizontal circular screen disc baffles. They proposed correlations for minimum fluidizing mass velocity in baffled fluidized beds with system parameters like particle size and density, fluid viscosity and density and the size of the screen opening relative to particle size as under-

$$G'_{mf} = \left[0.000692 + 0.00035\left(\frac{d_o}{d_p}\right)^{-0.31}\right]\left[d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \tag{2.19}$$

The above correlation was found to predict satisfactory result within the $d_o / d_p$ range of 2-52. Alternatively, the above equation was expressed as:

$$\frac{\left(Re'_{p,mf} - \mathrm{Re}_{p,mf}\right)}{Ga} = 0.00035\left(\frac{d_o}{d_p}\right)^{-0.3} \tag{2.20}$$

The values of minimum fluidizing mass velocity was found to be higher in the baffled (promoted) fluidized beds compared to the un-baffled ones, depending upon the size of the screen opening.

Kumar et al. [64] reported that minimum fluidization mass velocity was observed to be lower in a tapered bed with mechanical stirrer compared to that in a bed without a stirrer. They proposed the following correlations for the prediction of minimum fluidization mass velocity in terms of dimensionless groups:

## For a tapered bed without stirrer

$$\frac{d_p \phi_s G_{mf}}{\mu_f} = 0.136\left(\frac{h_s}{D_i}\right)^{1.2}\left[\frac{\rho_f\left(\rho_s - \rho_f\right) g \phi_s^3 d_p^3}{\mu_f^2}\right]^{0.6}\left(\tan\alpha\right)^{0.93} \tag{2.21}$$

**For a tapered bed with stirrer**

$$\frac{d_p\phi_s G_{mf}}{\mu_f} = 0.312\left[\frac{\rho_f\left(\rho_s-\rho_f\right)g\phi_s^3 d_p^3}{\mu_f^2}\right]^{0.63}$$

$$\times\left[\tan\alpha/2\right]^{0.008}\left[\frac{h}{h_s}\right]^{0.23}\left[\frac{L^2 N\rho_f}{\mu_f}\right]^{-0.103} \qquad (2.22)$$

### **2.2.**5 Pressure drop

The pressure drop through the bed is another important parameter which controls the channel and slug formation and thereby mixing of the bed material with the fluidizing fluid. At low flow rates in the packed bed, the pressure drop is approximately proportional to gas velocity upto the minimum fluidization condition. With a further increase in gas velocity, the packed bed suddenly unlocks (at the onset of minimum fluidization condition), resulting in a decrease in pressure drop. With gas velocities beyond minimum fluidization, the bed expands and gas bubbles are seen to rise resulting in nonhomogeneity in the bed. With the increase in gas flow, the pressure drop should remain unchanged but due to bubbling and slugging there is always a fluctuation in the pressure drop and it increases slightly [65]. Particularly for coarse particles, the mean total pressure drop across a slugging bed may continue to increase with gas velocity higher than at the minimum fluidization condition.

Particulate fluidization generally gives rise to a homogeneous fluidization. However, this ideal situation is not realized in practice and significant deviations have been observed. Couderc and Angelino [50] have demonstrated experimentally that channelling results in differences in the local pressure drop through the fluidized bed, particularly near minimum fluidization.

The baffle (promoter) spacing and size of the screen opening relative to particle size have got a significant effect on unit bed pressure drop under settled bed condition. However, under fluidized bed condition, the effect was less significant and the pressure drop values approach those for unbaffled (unpromoted) beds, specially for baffle spacing greater than 5 mm, and for baffle hole sizes 3-4 times greater than the particle size.

Takami and Takeshige [66] investigated the effect of perforated horizontal plates as internal baffles (promoters) on pressure fluctuation and reported that higher frequency of pressure fluctuation corresponded with better quality of fluidization.

Kumar et al. [67] proposed the following correlations for the prediction of pressure drop through a batch liquid-solid fluidized bed with co-axial vertical rod promoter:

**For unpromoted bed**

$$Eu = 74\left(\frac{h_s}{D_c}\right)^{1.98}\left(\frac{h_e}{D_c}\right)^{-2.23}\left(\frac{\rho_s}{\rho_f}\right)^{-0.3}\left(\frac{d_p}{D_c}\right)^{-0.80} \tag{2.23}$$

**For bed with rod promoter**

$$Eu = 15\left(\frac{h_s}{D_c}\right)^{2.79}\left(\frac{h_e}{D_c}\right)^{-2.20}\left(\frac{\rho_s}{\rho_f}\right)^{-0.66}\left(\frac{d_p}{D_c}\right)^{-1.23} \tag{2.24}$$

From experimental findings, Kar and Roy [68] gave the following correlations for the prediction of bed pressure drop in a gas-solid fluidized bed promoted with co-axial rod and co-axial disk type of promoters:

**For unpromoted bed**

$$\frac{\Delta p_b}{\rho_f U_f^2} = 0.0124\left(\frac{h_s}{D_c}\right)^{2.8}\left(\frac{h_e}{D_c}\right)^{-1.51}\left(\frac{d_p}{D_c}\right)^{-1.45}\left(\frac{\rho_s}{\rho_f}\right)^{0.66} \tag{2.25}$$

**For bed with co-axial rod type promoter**

$$\frac{\Delta p_b}{\rho_f U_f^2} = 0.003\left(\frac{h_s}{D_c}\right)^{2.19}\left(\frac{h_e}{D_c}\right)^{-2.15}\left(\frac{d_p}{D_c}\right)^{-1.3}\left(\frac{\rho_s}{\rho_f}\right)^{1.02} \tag{2.26}$$

**For bed with co-axial disk type promoter**

$$\frac{\Delta p_b}{\rho_f {U_f}^2} = 1.842\left(\frac{h_s}{D_c}\right)^{2.86}\left(\frac{h_e}{D_c}\right)^{-0.93}\left(\frac{d_p}{D_c}\right)^{-0.57}\left(\frac{\rho_s}{\rho_f}\right)^{0.34} \tag{2.27}$$

They observed lower pressure drop in case of a bed with disk promoter than in a bed with rod promoter.

It has been shown by Whitehead and Dent [69] that the initiation and maintenance of continuous solids motion adjacent to points of gas entry at a fluidized bed distributor is critically dependent on the pressure drop across the distributor. They recommended a high-pressure drop gas distributor to be generally more advantageous. This amounts to high power consumption. However, in the design of a gas distributor, a minimum pressure drop across the distributor ($\Delta p_d$), is to be maintained to ensure all the orifices functioning properly or, in other words, become active and provide a uniform gas flow at the bottom of the bed. The ratio of distributor- to-bed pressure drop at minimum fluidization velocity has usually been used as the criterion for multiorifice distributor design.

Yardim et al [70] observed the largest and smallest bed pressure drop in perforated and perforated-slanted plates respectively in empty bed. With loaded bed, they found 0.85 as the ratio (loaded/empty) of the calculated values of bed pressure drop for perforated-slanted and 1.02-1.9 as for perforated and nozzle type distributors respectively.

Saxena et al. [71] studied the effect of (i) porous plate distributor, (ii) two bubble cap distributors of different geometries and (iii) four Johnson screen distributors of varying percentage open area on pressure drop and correlated by single equation as:

$$\frac{2g_c \Delta p_d}{\rho_f V_o^2} = C_1 \left( \frac{D_c U_f \rho_f}{\mu_f g_c} \right)^{C_2} \tag{2.28}$$

They derived the following general conclusions-

a) The distributor pressure drop increases with fluidizing velocity, decreases with percentage open area of the distributor plate, and is independent of the bed weight or bed height for a given distributor.
b) The pressure drop ratio $\left(\Delta p_d / \Delta p_b\right)$ increases rapidly with increase in fluidization velocity. The value of this pressure ratio at minimum fluidization depends the on bed height, and its degree depends sensitively on distributor design.

Briens et al. [72] felt the importance of good grid design for satisfactory performance of large gas fluidized beds and the accurate measurement of grid pressure drop. They concluded that the presence of fluidized solids can increase the pressure drop through the perforated plate distributors by as much as 100%. The pressure drop increase was still larger than 25% at higher gas velocities, for a grid- to- bed pressure drop ratio of 0.4. They investigated the various causes for this increase and concluded that it was primarily due to the backflow of fluidized solids into the grid holes under the influence of waves at the bed surface.

Sathiyamoorthy and Rao [55] concluded that the choice of the distributor-to-bed pressure drop ratio ($\Delta p_d / \Delta p_b$) for stable operation of a fluidized bed depends on the $U_M / U_{mf}$ ratio. Based on the analysis of the gas-solid fluidized bed for its stable operation in terms of all operating orifices and uniform fluidization, Sathiyamoorthy and Rao (loc. cit.) obtained an expression to determine pressure drop ratio as given below:

$$\frac{\Delta p_d}{\Delta p_b} = 2\left(\frac{U_{mf}}{U_M - U_{mf}}\right)^2 \tag{2.29}$$

or, more precisely using the experimental correlation as

$$\frac{\Delta p_d}{\Delta p_b} = 2.7\left(\frac{U_{mf}}{U_M - U_{mf}}\right)^{2.32} \tag{2.30}$$

Swain et al. [73] developed a correlation for the prediction of distributor-to-bed pressure drop ratio taking distributors of varying open area ranging from 2.28 to 6.36% of the column sectional area. Using the distributors with 3 mm diameter orifices distributed in two zones viz. the annular and the central with equal open area they gave the following correlation:

$$\frac{\Delta p_b}{\Delta p_d} = 2.604\times10^3 \left(\frac{G_f}{G_{mf}}\right)^{-0.68} \left(\frac{h_s}{D_c}\right)^{1.34} \left(\frac{d_p}{D_c}\right)^{0.75} \left(\frac{A_{do}}{A_c}\right)^{1.85}$$

$$X\left(\frac{A_A}{A_c}\right)^{-0.54} \left(\frac{\rho_s}{\rho_f}\right)^{0.30} \tag{2.31}$$

They observed that an increase in the free flow area for air through the distributor causes more and more non-uniformity in fluidization.

Ghosh and Saha [74] carried their studies with five distributors covering a percentage of open area from 0.35 to 2.77 to obtain the fractional number of active orifices through visual observations. The satisfactory agreement of the observed and predicted value of fractional number of active orifices suggests that the theory of Yue and Kolaczkowski [75] can be used in the design of multiorifice distributor up to a percentage of open area of 2.73 and for Geldart's D type particles. An empirical equation was proposed for $\Delta p_{d,\min}$ relating it with bed and distributor characteristics and operational parameters for the safe design of distributors as below:

$$\Delta p_{d,\min} = 3.468 \frac{h_{mf}^{0.693} d_p^{1.08} \varphi^{-0.371}}{1 - U_{mf} U_m} \tag{2.32}$$

Yue and Kolaczkowski (loc. cit.) based on their experimental results, proposed a model for the minimum pressure drop necessary to ensure uniform gas distribution as below:

$$\Delta p_{d,\min} - \Delta p_{d,mf} = \Delta p_{b,mf} \left( \overline{\varepsilon_b} + 0.363 \frac{H_s}{h_{mf}} \right) \tag{2.33}$$

They concluded that the minimum distributor pressure drop required to ensure uniform gas distribution in a fluidized bed is dependent on the operating condition and bed characteristics.

Feng et al. [41] concluded that static pressure is higher in areas where bubbles are frequent and large.

Based on experimental work on distributors of varying orifice sizes, number and pitch, arranged in triangular pattern, Chyang and Huang [76] proposed an approach to modify the orifice equation as below:

$$\Delta p_{d,mf} = \frac{(1 + 0.716) \rho_f U_{o,mf}^2}{2 C_D^2} \tag{2.34}$$

He concluded that the pressure drop across a perforated plate distributor measured in the presence of material was higher than that measured in an empty bed.

### 2.2.6 Bed expansion

Expansion of gas-solid fluidized beds may in general result from the volume occupied by bubbles and from increase in voidage of the dense phase. If the average volume fraction occupied by bubbles in the entire bed is $\varepsilon_b$ while the average dense phase voidage is $\varepsilon_b$, then, ignoring the volume of particles dispersed in bubbles or in the freeboard, the particle balance leads to

$$\frac{h_{av}}{h_{mf}} = \frac{\left(1-\varepsilon_{mf}\right)}{\left(1-\varepsilon_d\right)\left(1-\varepsilon_b\right)} \tag{2.35}$$

For Group A powders [26] and high pressure fluidized beds, some expansion of the dense phase occurs between minimum fluidization and minimum bubbling. For Group B and D powders, the dense phase voidage remains very close to $\varepsilon_{mf}$, so that bed expansion arises entirely from the volume occupied by bubbles i.e.

$$\frac{h_{av}}{h_{mf}} = \varepsilon_b \tag{2.36}$$

or,

$$R = \frac{h_{av} - h_{mf}}{h_{mf}} = \frac{\varepsilon_b}{1-\varepsilon_b} \tag{2.37}$$

Godard and Richardson [29] proposed a correlation for bed expansion in freely bubbling fluidized beds as follows:

$$R - 1 = \frac{U_f - U_{mf}}{m\left(0.35\sqrt{gD_c}\right)} \tag{2.38}$$

where ‘m’ is a variable which accounts for any excess gas passing through the homogeneous phase.

Bed expansion ratio increases with increasing value of excess velocity and for distributors which give smaller bubbles [77] and [71]. Very poor distributors which lead to channelling condition rather than bubbling reduce bed expansion. Fractional expansion is generally greater for smaller values of $h_{mf}$ [71]. Group A particle tend to expand further than group B powders. Xavier et al. [78] extended the above results to beds in which tube bundles occupy an appropriate fraction of the bed volume. Tubes or baffles (promoters) may either increase or decrease bed expansion, depending on their effect on bubble size, coalescence pattern and channelling.

The expanded height of a slugging bed may be estimated from a result closely analogous to equation for the bubbling beds, but with the maximum bed height $h_{max}$ in place of the average expanded height [79].

$$R_{\max} = \frac{h_{\max} - h_{mf}}{h_{mf}} = \frac{U_f - U_{mf}}{U_{s\infty}} \tag{2.39}$$

It is assumed here that a slug rises through the whole bed with velocity given by Matsen et al. [48] as in Eq. 2.12.

Eq. 2.35 requires observing the bed surface to note the maximum height reached. It is only necessary for one slug to meet this assumption during the period of observation for $h_{\max}$ to agree with this Eq. 2.39. Matsen et al. (loc. cit.) found that Eq. 2.39 agree with a wide range of data. Frequently the first slug after the start- up meets this assumption, so that Eq. 2.39 describes the first maximum bed depth corresponding to eruption of the first slug [80]. Bed height at subsequent eruptions may be significantly lower, because bubble coalescence in the part of the bed immediately above the distributor, where slug flow is developing, and slugging in the upper part of the bed, increases the velocity above the value given by Eq. 2.12.

Singh [81, 82] studied the effect of various system parameters on bed expansion ratio in case of unpromoted columnar and non-columnar beds and proposed the following correlations:

**For cylindrical bed**

$$R = 2.55\left(\frac{d_p}{D_c}\right)^{0.11}\left(\frac{D_c}{h_s}\right)^{0.31}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.18} \tag{2.40}$$

**For semi cylindrical bed**

$$R = 5.46\left(\frac{d_p}{D_c}\right)^{0.26}\left(\frac{D_c}{h_s}\right)^{0.03}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.21} \tag{2.41}$$

**For hexagonal bed**

$$R = 2.422\left(\frac{d_p}{D_c}\right)^{0.12}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.35} \tag{2.42}$$

**For square bed**

$$R = 6.09\left(\frac{d_p}{D_c}\right)^{0.24}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.27} \tag{2.43}$$

Claus et al. [14] concluded from the investigation that, in batch systems, the expansion is given by a Capes and McMillhinney [20] type power law and the contribution of the packing to support the bed can be upto 20 percent of the weight of solid.

Jin et al. [9] concluded that the equivalent diameter of the pagoda shaped baffle (promoter) is likely to have an effect on the bed expansion and proposed an equation for the determination of bed expansion ratio of the fluidized bed as-

$$R - 1 = \frac{\left(0.05 + 0.839 w_o^2\right)}{d_p^{0.6}} \tag{2.44}$$

Kumar and Roy [11] investigated the effect of co-axial rod and blade type of promoters on expansion ratio. They proposed the modified version of Bernek and Sokol [83] correlations, for the two regime of $G_R$ as under:

In the range $0 < G_R \le 0.15$:

**For beds with and without promoter**

$$\frac{1}{R} = 0.433\left(G_R\right)^{-0.28} \tag{2.45}$$

In the range $0.15 < G_R \le 1.0$

**For unpromoted bed**

$$\frac{1}{R} = 0.141\left(G_R\right)^{-0.88} \tag{2.46}$$

**For bed with co-axial rod type promoter**,

$$\frac{1}{R} = 0.239\left(G_R\right)^{-0.63} \tag{2.47}$$

**For bed with co-axial blade type promoter,**

$$\frac{1}{R} = 0.348\left(G_R\right)^{-0.46} \tag{2.48}$$

They observed that the use of co-axial rod and blade type of promoters are quite effective to dampen the bed fluctuation and thereby reduce the expanded bed height when compared with unpromoted fluidized bed with identical system parameters especially in the second regime. Also, the dampening effect of blade type promoter was found to be more as compared to the co-axial rod promoter.

Saxena et al. [71] observed that the bed expansion ratio increases with the increase in excess fluidizing mass velocity and decreases with increase in initial static bed height or weight. The quantitative magnitude of these variations have been found to be dependent on the distributor design.

### 2.2.7 Bed fluctuation

For gas flow more than the minimum fluidization velocity, the top of the fluidized bed may fluctuate considerably. The extent of the fluctuation and its estimation becomes important while specifying the height of a fluidizer. The fluctuation may be defined as the ratio of the highest and the lowest level of the top of the bed for any fluidizing gas mass velocity. This ratio is termed as the fluctuation ratio [57].

Bed fluctuation and fluidization quality being inter-related, consistent efforts have been made to correlate fluctuation ratio in terms of static and dynamic parameters of the system.

Kawabata et al. [63] have studied the bed height fluctuation under pressure in a two-dimensional bed. They plotted the bed height fluctuation ratio at various pressure against excess gas velocity and noted that the fluctuation seems to be little affected by changes in pressure regardless of the particle size.

Maiden attempt to correlate fluctuation ratio to bed characteristics was made by Leva [60] as under

$$r = e^{m} \frac{G_f - G_{mf}}{G_{mf}} \tag{2.49}$$

where the slope 'm' was related to particle diameter. Beyond certain limiting value of $\frac{G_f - G_{mf}}{G_{mf}}$, the top oscillation are also caused by slugging. The fluctuation ratio pertaining to the slugging zone follows smoothly from the non-slugging zone. Since slugging is to be affected by the 'aspect ratio', the fluctuation ratio is dependent on this also [57].

Singh [81, 82] proposed the following correlations for the prediction of bed fluctuation ratio in case of unpromoted columnar (cylindrical) and non-columnar beds:

**For cylindrical bed**

$$r = 1.95\left(\frac{d_p}{D_c}\right)^{0.04}\left[\left(\frac{D_c}{h_s}\right)\times\left(\frac{\rho_f}{\rho_s}\right)\right]^{0.04}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.05} \tag{2.50}$$

**For semi cylindrical bed**

$$r = 2.323\left(\frac{d_p}{D_c}\right)^{008}\left[\left(\frac{D_c}{h_s}\right)\times\left(\frac{\rho_f}{\rho_s}\right)\right]^{0.04}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.07} \tag{2.51}$$

**For hexagonal bed**

$$r = 2.3\left(\frac{d_p}{D_c}\right)^{0.06}\left[\left(\frac{D_c}{h_s}\right)\times\left(\frac{\rho_f}{\rho_s}\right)\right]^{0.05}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.06} \tag{2.52}$$

**For square bed**

$$r = 6.09\left(\frac{d_p}{D_c}\right)^{0.09}\left[\left(\frac{D_c}{h_s}\right)\times\left(\frac{\rho_f}{\rho_s}\right)\right]^{0.04}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.08} \tag{2.53}$$

Based on experimental investigations, Biswal et al. [84] suggested the following correlations for the prediction of bed fluctuation ratio in conical beds:

## For homogeneous mixture

$$r = 9.8\times10^{2}\left(\frac{G_f}{G_{mf}}\right)^{1.06}\left(\frac{D_c}{\bar{d}_{pm}}\right)^{-1.97}\left(\frac{h_s}{D_c}\right)^{-1.35}(\tan\alpha)^{-0.25} \tag{2.54}$$

## For heterogeneous mixtures

$$r = 0.44\left(\frac{G_f}{G_{mf}}\right)^{0.58}\left(\frac{\bar{d}_{pm}}{D_c}\right)^{0.06}\left(\frac{\rho_{sm}}{\rho_f}\right)^{0.10}(\tan\alpha)^{-0.17} \tag{2.55}$$

For the case of conical bed of monosize regular and irregular particles, Biswal et al. [85, 86] proposed the following correlations for the bed fluctuation ratio:

## For regular particles

$$r = 1.43\left(\frac{h_s}{D_c}\right)^{-0.145}\left(\frac{D_c}{d_p}\right)^{0.09}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.153} \tag{2.56}$$

## For irregular particles

$$r = 9.48\left(\frac{D_c}{h_s}\right)^{-0.83}\left(\frac{d_p}{D_i}\right)^{0.27}\left(\frac{\rho_s}{\rho_f}\right)^{-0.15}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.32} \tag{2.57}$$

Agarwal and Roy [87] developed the following correlations to predict fluctuation ratio for columnar fluidized beds with and without promoters and also for conical fluidized bed (unpromoted):

## For cylindrical beds without baffles (promoters)

$$r = 0.045\left(\frac{G_f}{G_{mf}}\right)^{1.49}\left(\frac{d_p}{D_c}\right)^{0.43}\left(\frac{D_c}{h_s}\right)^{-0.59}\left(\frac{\rho_s}{\rho_f}\right)^{-0.50} \tag{2.58}$$

**For baffled (promoted) cylindrical beds**

**(a) With vertical baffle (promoter)**

$$r = 0.59\left(\frac{G_f}{G_{mf}}\right)^{1.01}\left(\frac{d_p}{D_c}\right)^{-0.12}\left(\frac{D_c}{h_s}\right)^{-0.20}\left(\frac{\rho_s}{\rho_f}\right)^{-0.02} \tag{2.59}$$

**(b) With stirrer type baffle (promoter)**

$$r = 2.49\left(\frac{G_f}{G_{mf}}\right)^{1.75}\left(\frac{d_p}{D_c}\right)^{-0.07}\left(\frac{D_c}{h_s}\right)^{-0.29}\left(\frac{\rho_s}{\rho_f}\right)^{-0.25} \tag{2.60}$$

**For Conical beds**

$$r = 0.44\left(\frac{G_f}{G_{mf}}\right)^{0.58}\left(\frac{d_p}{D_c}\right)^{0.06}\left(\frac{\rho_s}{\rho_f}\right)^{-0.50}\left(\tan\alpha\right)^{-0.17} \tag{2.61}$$

They observed reduced bed fluctuation in baffled (promoted) beds in the order of: cylindrical with vertical baffles, cylindrical with stirrer type of baffles. They further observed that the bed fluctuation was less for conical bed as compared with cylindrical ones.

Kar and Roy [68] observed that the fluctuation ratio for unpromoted bed was quite high as compared to beds with rod and disk promoters and proposed the following correlations for prediction of bed fluctuation ratio in gas-solid fluidized beds with rod and disk promoters:

## For unpromoted bed

$$r = 0.003\left(\frac{h_s}{D_c}\right)^{0.11}\left(\frac{d_p}{D_c}\right)^{-0.05}\left(\frac{\rho_s}{\rho_f}\right)^{1.08}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.35} \tag{2.62}$$

## For bed with co-axial rod promoter

$$r = 0.004\left(\frac{h_s}{D_c}\right)^{0.15}\left(\frac{d_p}{D_c}\right)^{-0.29}\left(\frac{\rho_s}{\rho_f}\right)^{0.29}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.30} \tag{2.63}$$

## For bed with co-axial disk promoter

$$r = 0.87\left(\frac{h_s}{D_c}\right)^{0.04}\left(\frac{d_p}{D_c}\right)^{-0.04}\left(\frac{\rho_s}{\rho_f}\right)^{0.02}\left(\frac{G_f - G_{mf}}{G_{mf}}\right)^{0.04} \tag{2.64}$$

For identical system parameters, bed fluctuation ratio was found to be lower for bed with disk type than with rod type promoter.

Incorporating distributor parameters, Swain et al. [73] proposed a correlation for bed fluctuation ratio as:

$$r = 3.136\left(\frac{G_f}{G_{mf}}\right)^{0.60}\left(\frac{h_s}{D_c}\right)^{-0.35}\left(\frac{d_p}{D_c}\right)^{-0.43}\left(\frac{A_{do}}{A_c}\right)^{0.24}$$

$$X\left(\frac{A_A}{A_c}\right)^{-0.11}\left(\frac{\rho_s}{\rho_f}\right)^{-0.23} \tag{2.65}$$

A little information is available on the effect of promoters on bed pressure drop, minimum fluidizing mass velocity and other fluidization related parameters specially in terms of bed expansion and fluctuation. Most of the available literature explain qualitatively some effect of turbulence promoters on the parameters effecting the quality of fluidization.

In the present work extensive experimental investigations have been carried out to study the effect of promoters viz. four number of rod promoter and eleven number of disk promoters of varying configuration and specification and five number of distributors in addition to other system variables on fluidization quality in terms of minimum fluidization velocity, pressure drop, bed expansion and fluctuation. The effect of turbulence promoters on minimum fluidization velocity, bed pressure drop, bed expansion and bed fluctuation have been expressed quantitatively with the help of dimensional analysis approach.

## 2.3 Application of Artificial Neural Network (ANN)

Computation through neural networks is one of the recently growing areas of artificial intelligence. Neural networks are promising due to their ability to learn highly nonlinear relationship. An artificial neural network based model has been defined in literature as a computing system made up of a number of simple, highly interconnected processing elements, which processes information by its dynamic state response to external inputs [88, 89]. The back propagation network which is the most well known and widely used among the current types of neural network system [90], has been used in the present study. Several applications of ANN for modelling of nonlinear process systems and subsequent control have been reported [91-99].

In the present case, a software package for artificial neural network developed by Rao & Rao [96] using back propagation algorithm has been used. Al-together twelve ANN-models: four each for the prediction of bed expansion ratio, bed fluctuation ratio and distributor-to-bed pressure drop ratio respectively for unpromoted and three different types of promoted beds have been developed. The predicted values of the result using ANN-models have been used to compare with the results obtained through corresponding dimensional analysis.

## Nomenclature

| | |
|---|---|
| $A_A$ | annulus opening area of distributor, $L^2$ |
| $A_c$ | cross sectional area of column, $L^2$ |
| $A_{do}$ | open area of distributor, $L^2$ |
| $a_o$ | area of orifice, $L^2$ |
| $C_1$, $C_2$ | numerical constants in Eq. 2.28 |
| $C_D$ | orifice discharge coefficient |
| $D_c$ | column diameter, L |
| $D_i$ | diameter of the bed at the inlet, L |
| $d_b$ | bubble diameter, L |
| $d_{bm}$ | maximum bubble size, $0.652\left[A_c\left(U_f-U_{mf}\right)\right]^{2/5}$, L |
| $d_{bo}$ | bubble size at origin, $0.00376\left(U_f-U_{mf}\right)^2$, L |
| $d_o$ | screen opening, L |
| $d_p$ | particle size, L |

| | |
|---|---|
| $\bar{d}_{pm}$ | average particle size in case of mixture, $\left(1/\sum \frac{X_i}{d_{si}}\right)$, L |
| $\bar{d}_s$ | mean surface diameter, L |
| $Fr_{mf}$ | Froude number at minimum fluidization, $U_{mf}^2 / d_p g$ |
| $E_u$ | Euler number, $\Delta p_b / \left(\rho_f U_f^2\right)$ |
| $Ga$ | Galilleo number, $\left[d_p^3 \rho_f \left(\rho_s - \rho_f\right) g\right] / \mu_f$ |
| $G_f$ | fluidization mass velocity, $ML^{-2}T^{-1}$ |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted beds, $ML^{-2}T^{-1}$ |
| $G'_{mf}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $G_R$ | mass velocity ratio, $\left(G_f - G_{mf}\right)/\left(G_s - G_{mf}\right)$ |
| $G_t$ | terminal mass velocity, $ML^{-2}T^{-1}$ |
| $g$ | acceleration due to gravity, $LT^{-2}$ |
| $g_c$ | conversion factor, 980g cm/(g wt.)sec$^2$ |
| $H_s$ | height of spout or jet, L |
| $h$ | bed height above distributor level, L |
| $h_{av}$ | average bed height = $\left(h_{\max} + h_{\min}\right)/2$, L |
| $h_e$ | expanded bed height, L |
| $h_{\max}$ | maximum height of fluidized bed, L |
| $h_{mf}$ | bed height at minimum fluidization, L |
| $h_{\min}$ | minimum height of fluidized bed, L |
| $h_o$ | a measure of the initial bubble size, which characterizes of the distributor and is effectively zero for porous plate, L |
| $h_s$ | initial static bed height, L |

| | |
|---|---|
| $N$ | revolutions per minute, $T^{-1}$ |
| $K_{mb}$ | constant at minimum bubbling, L |
| $n$ | no. of orifices in the distributor plate |
| $P$ | pressure, $ML^{-1}T^{-2}$ |
| $R$ | bed expansion ratio, $h_{av}/h_s$ |
| $R_c$ | critical value of pressure drop ratio |
| $\mathrm{Re}_{p,mf}$ | particle Reynolds number at minimum fluidization, $d_p U_{mf} \rho_f / \mu_f$ |
| $Re'_{p,mf}$ | particle Reynolds number at minimum fluidization in promoted bed |
| $r$ | bed fluctuation ratio, $h_{\max}/h_{\min}$ |
| $U$ | velocity ratio, $(U_f - U_{mf})/(U_t - U_{mf})$ |
| $U_f$ | superficial velocity of the fluidizing gas, $LT^{-1}$ |
| $U_M$ | superficial velocity at which all orifices become operative, $LT^{-1}$ |
| $U_{mb}$ | minimum bubbling velocity, $LT^{-1}$ |
| $U_{mf}$ | minimum superficial fluidization velocity, $LT^{-1}$ |
| $U_{ms}$ | minimum slugging velocity, $LT^{-1}$ |
| $U_o$ | gas velocity through distributor orifices, $LT^{-1}$ |
| $U_{o,mf}$ | gas velocity through distributor orifices at minimum fluidization, $LT^{-1}$ |
| $U_s$ | rise velocity of slug in a freely slugging bed, $LT^{-1}$ |
| $U_{s\infty}$ | rise velocity of single particle, $LT^{-1}$ |
| $U_t$ | terminal velocity of the particle, $LT^{-1}$ |
| $V_o$ | orifice velocity, $LT^{-1}$ |

| | |
|---|---|
| $w_o$ | linear velocity in the fluidized bed, $LT^{-1}$ |
| $X_f$ | fraction of fines. |
| $X_i$ | weight fraction of particle of diameter $d_s$ |

***Greek letters***

| | |
|---|---|
| $\bar{\varepsilon}_b$ | average bubble voidage |
| $\alpha$ | apex angle of cone (conical / tapered bed) |
| $\varphi$ | orifice density, $na_o / A_c$ |
| $\varepsilon_b$ | void fraction occupied by bubbles |
| $\varepsilon_d$ | void fraction in dense phase |
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\mu_f$ | viscosity of fluid, $ML^{-1}T^{-1}$ |
| $\varepsilon_{mf}$ | void fraction in bed at minimum fluidization condition |
| $\Delta p_b$ | bed pressure drop, $ML^{-1} T^{-2}$ |
| $\Delta p_{b,mf}$ | fluidized bed pressure drop at minimum fluidization condition, $ML^{-1} T^{-2}$ |
| $\Delta p_d$ | distributor pressure drop, $ML^{-1} T^{-2}$ |
| $\Delta p_{d,\min}$ | minimum distributor pressure at which all orifices become active, $ML^{-1} T^{-2}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |
| $\phi_s$ | sphericity of the particle |
| $\rho_{sm}$ | material density in case of mixture, $ML^{-3}$ |

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# CHAPTER III

# Experimental aspects

## 3.1 Experimental Set-up

The experimental set-up consists primarily of the following major components (Fig. 3.1 and Plates 3.1):

1. Air compressor
2. Air receiver
3. Constant pressure tank
4. Silica-gel column
5. Rotameters
6. Calming section
7. Air distributor
8. Fluidizer
9. Manometer
10. Pressure gauge
11. Promoter

### Air compressor

It is a K.G. type stationary water-cooled air compressor, driven by 5.5 kW 3-phase induction motor.

## Air receiver

It is a horizontal pressure vessel provided with a pressure gauge of range 0 to 7.0 $kg/cm^2$ (686.7 kPa) and a safety valve.

## Constant pressure tank

It is of the same size as that of the receiver, with flat ends. The purpose of using this tank in the line is to dampen the pressure fluctuations and to supply compressed air to the system at a constant pressure. It is also provided with a pressure gauge of range 0 to 5.6 $kg/cm^2$ (549.36 kPa). Constant pressure tank used in the set up maintained a constant pressure of 2.8 $kg/cm^2$ (274.68 kPa).

## Silica-gel column

The compressed air from the constant pressure tank is passed through this column, fitted with silica-gel to dry the air before being used in the system.

## Rotameters

Two rotameters -one for the measurement of lower range (0 to 8 kg/hr) and the other for the higher range of flow (beyond that of lower range rotameter) have been used.

### (a) Lower range

It is graduated to read the maximum flow rate of 3960.86 $kg/(m^2$- hr) as against 100% range of the rotameter.

### (b) Higher range

It is graduated to read the maximum flow rate of 6250.57 kg/($m^2$- hr) as against 50% range of the rotameter.

### Calming section

The compressed and dried air from the rotameters is passed through a conical section filled with 5 mm diameter glass-balls, supported on a coarse screen which serves as the calming section. This dampens the turbulence in flow and helps smoothening of pressure fluctuations in the inlet air.

### Air distributor

The calming section is followed by a GI plate of 1 mm thickness having 37 nos. of orifices placed in an equilateral triangular pattern at a pitch of 7.5 mm to act as an air distributor which facilitate uniform air entry to the fluidizer. A mild steel wire mesh is placed over the distributor to prevent the entry of materials into the calming section. Altogether five distributors (Fig. 3.2 and Plate 3.2) with opening area of 12.9%, 8.96%, 5.74%, 3.23% and 1.43% of the column section have been used in the experiment.

### Fluidizer

It is a cylindrical column of 5.08 cm I. D. and 100 cm. length made up of perspex material. It is provided with flanges of the same material. Three pressure tappings-two just below and above the distributor, and the third from the top of the bed, have been taken.

## Manometers

Two differential manometers with carbon tetra-chloride as the manometric liquid have been used to record the distributor and the total (bed + distributor) pressure drop.

## Promoter

Three types of promoter viz. rod, disk and blade have been used in the study. The promoters are placed at one cm above the distributor level with the help of two clamps fixed in the opposite directions at the top of the fluidizer. The details of promoter details are as under**:**

### (a) Rod promoters

Four number of rod promoters each having a 6.1 mm central rod and respectively 4, 8, 12 and 16 number of 4 mm radial rods placed in concentric circles (Fig. 3.3 and Plate 3.3) have been used.

### (b) Disk promoters

Seven number of disk promoters with varying disk thickness and disk diameter (Fig. 3.4 and Plate 3.4) have been used. The disks of each disk promoter have been fixed to a 6.1 mm diameter central rod at equal spacing of 38.6 mm c/c and at an inclination of $10^o$ with the horizontal alternatively in the opposite directions to minimize the accumulation of bed materials over the disks.

### (c) Blade promoter

One blade type of promoter (Fig. 3.5 and Plate 3.5) having total blockage equal to that of one each of the rod and disk type promoters has also been used in the investigation.

The blades have been fixed to a 6.1 mm diameter central rod at equal spacing of 45.4 mm c/c and at an inclination of $10^o$ with the horizontal alternatively in the opposite directions to minimize the accumulation of bed materials over the blades.

## 3.2 Experimental procedure for collection of data

The rotameters have been calibrated first with the help of standard dry gas meter at normal temperature and pressure (Figs. 3.6 and 3.7). To begin with, blank runs (without bed material) have been conducted with and without promoter. The bed pressure drop in both the cases have been found to be inappreciable over the entire range of flow-rate maintained during the study. A known amount of bed material is charged to the column from top. The reproducible static bed height has been obtained after fluidizing the bed gradually and then allowing it to settle slowly atleast three times. The compressed dry air has been admitted to the column from the constant pressure tank maintained at a pressure of 2.8 kg/cm$^2$ (274.68 kPa). The distributor pressure drop and the total (bed + distributor) pressure drop data have been recorded against the gradual change of flow rate till fluidization condition is attained. In the fluidized state, the fluctuation for the top of the bed (maximum and minimum levels) has been noted alongwith the rotameter and manometer readings for each value of the air flow rate. The same has been repeated with varying particle size, density, static bed height and distributor for promoted as well as unpromoted beds and are presented in appendix 1. The scope of the present investigation is presented in Table 3.1.

The porosity values for initial static beds with different bed materials of varying sizes have been obtained by measuring the volume of void in the respective beds. For this, the bed has been completely saturated with water and then the volume of water occupied by the pores has been collected and measured. With the known values of porosity, the sphericity has been calculated using Leva's [1] equation which is as under:

$$\frac{1-\varepsilon}{\phi_s} = 0.231 \ \log d_p + 1.417 \tag{3.1}$$

where $d_p$ is the particle size in feet.

The values of terminal velocity used in the analysis have been obtained by using a correlation given by Chattopadhyay [2] and are presented in appendix-2.

## 3.3 Data processing (with respect to chapters 4, 5 & 6)

The experimental data for bed fluctuation and bed pressure drop in the fluidized state with varying flow rate, particle size, particle density, initial static bed height and distributor opening both for promoted and unpromoted beds have been collected. These data have been processed to predict the output viz. bed expansion, fluctuation and pressure drop by the following two methods:

(i) Conventional dimensional analysis, and

(ii) Artificial neural network (ANN) models.

### 3.3.1 Dimensional analysis

The following system variables which are likely to influence the output of the system viz. bed expansion, fluctuation and pressure drop, have been considered in the development of the correlations:

**Flow properties**

fluidization mass velocity ( $G_f$ )

minimum fluidization mass velocity ( $G_{mf}$ )

terminal mass velocity ( $G_t$ )

**Bed properties**

column diameter ( $D_c$ )

initial static bed height ( $h_s$ )

**Material properties**

particle size ( $d_p$ )

particle density ( $\rho_s$ )

**Fluid property**

density of fluid ( $\rho_f$ )

**Distributor properties**

orifice diameter ( $d_o$ )

open area of distributor ( $A_{do}$ )

**Rod promoter property**

equivalent diameter of the bed ( $D_e = 4Ao / P$ )

**Disk promoter properties**

disk diameter ( $D_k$ )

disk thickness ( $t$ )

Using dimensional analysis approach, the above system variables have been grouped into following non-dimensional parameters as:

**Flow parameters**

$G_R$ (mass velocity ratio) for bed expansion and fluctuation

$G_{mrf}$ (reduced fluidization mass velocity) for pressure drop ratio

**Bed parameter:** $h_s / D_c$

**Material parameters:** $\rho_s / \rho_f$ , $d_p / d_o$

**Distributor parameter:** $A_{do} / A_c$

**Rod promoter parameter:** $D_e / D_c$

**Disk promoter parameters:** $t / D_c$ , $D_k / D_c$

These non-dimensional system parameters have been related with different output of the system as below:

A. Modified expansion ratio ($R^{'}$)

**Unpromoted bed**

$$R^{'} = K_1 \left[ (G_R)^{a_1} \left( \frac{\rho_s}{\rho_f} \right)^{b_1} \left( \frac{A_{do}}{A_c} \right)^{c_1} \left( \frac{d_p}{d_o} \right)^{d_1} \left( \frac{h_s}{D_c} \right)^{e_1} \right]^{n_1} \tag{3.2}$$

**Bed with rod promoter**

$$R^{'} = K_2 \left[ (G_R)^{a_2} \left( \frac{\rho_s}{\rho_f} \right)^{b_2} \left( \frac{A_{do}}{A_c} \right)^{c_2} \left( \frac{d_p}{d_o} \right)^{d_2} \left( \frac{h_s}{D_c} \right)^{e_2} \left( \frac{D_e}{D_c} \right)^{f_2} \right]^{n_2} \tag{3.3}$$

**Bed with disk promoter**

$$R^{'} = K_3 \left[ (G_R)^{a_3} \left( \frac{\rho_s}{\rho_f} \right)^{b_3} \left( \frac{A_{do}}{A_c} \right)^{c_3} \left( \frac{d_p}{d_o} \right)^{d_3} \left( \frac{h_s}{D_c} \right)^{e_3} \left( \frac{t}{D_c} \right)^{g_3} \left( \frac{D_k}{D_c} \right)^{h_3} \right]^{n_3} \tag{3.4}$$

**Bed with blade promoter**

$$R^{'} = K_4 \left[ (G_R)^{a_4} \left( \frac{\rho_s}{\rho_f} \right)^{b_4} \left( \frac{A_{do}}{A_c} \right)^{c_4} \left( \frac{d_p}{d_o} \right)^{d_4} \left( \frac{h_s}{D_c} \right)^{e_4} \right]^{n_4} \tag{3.5}$$

B. Modified fluctuation ratio ($r^{'}$)

**Unpromoted bed**

$$r^{'} = K_5 \left[ (G_R)^{a_5} \left( \frac{\rho_s}{\rho_f} \right)^{b_5} \left( \frac{A_{do}}{A_c} \right)^{c_5} \left( \frac{d_p}{d_o} \right)^{d_5} \left( \frac{h_s}{D_c} \right)^{e_5} \right]^{n_5} \tag{3.6}$$

**Bed with rod promoter**

$$r^{'} = K_6 \left[ (G_R)^{a_6} \left( \frac{\rho_s}{\rho_f} \right)^{b_6} \left( \frac{A_{do}}{A_c} \right)^{c_6} \left( \frac{d_p}{d_o} \right)^{d_6} \left( \frac{h_s}{D_c} \right)^{e_6} \left( \frac{D_e}{D_c} \right)^{f_6} \right]^{n_6} \tag{3.7}$$

**Bed with disk promoter**

$$r^{'} = K_7 \left[ (G_R)^{a_7} \left( \frac{\rho_s}{\rho_f} \right)^{b_7} \left( \frac{A_{do}}{A_c} \right)^{c_7} \left( \frac{d_p}{d_o} \right)^{d_7} \left( \frac{h_s}{D_c} \right)^{e_7} \left( \frac{t}{D_c} \right)^{g_7} \left( \frac{D_k}{D_c} \right)^{h_7} \right]^{n_7} \tag{3.8}$$

**Bed with blade promoter**

$$r^{'} = K_8 \left[ (G_R)^{a_8} \left( \frac{\rho_s}{\rho_f} \right)^{b_8} \left( \frac{A_{do}}{A_c} \right)^{c_8} \left( \frac{d_p}{d_o} \right)^{d_8} \left( \frac{h_s}{D_c} \right)^{e_8} \right]^{n_8} \tag{3.9}$$

C. Distributor-to-bed pressure drop ratio $\left(\frac{\Delta p_d}{\Delta p_b}\right)$

**Unpromoted bed**

$$\frac{\Delta p_d}{\Delta p_b} = K_9\left[\left(G_{mrf}\right)^{a_9}\left(\frac{\rho_s}{\rho_f}\right)^{b_9}\left(\frac{A_{do}}{A_c}\right)^{c_9}\left(\frac{d_p}{d_o}\right)^{d_9}\left(\frac{h_s}{D_c}\right)^{e_9}\right]^{n_9} \tag{3.10}$$

**Bed with rod promoter**

$$\frac{\Delta p_d}{\Delta p_b} = K_{10}\left[\left(G_{mrf}\right)^{a_{10}}\left(\frac{\rho_s}{\rho_f}\right)^{b_{10}}\left(\frac{A_{do}}{A_c}\right)^{c_{10}}\left(\frac{d_p}{d_o}\right)^{d_{10}}\left(\frac{h_s}{D_c}\right)^{e_{10}}\left(\frac{D_e}{D_c}\right)^{f_{10}}\right]^{n_{10}} \tag{3.11}$$

**Bed with disk promoter**

$$\frac{\Delta p_d}{\Delta p_b} = K_{11}\left[\left(G_{mrf}\right)^{a_{11}}\left(\frac{\rho_s}{\rho_f}\right)^{b_{11}}\left(\frac{A_{do}}{A_c}\right)^{c_{11}}\left(\frac{d_p}{d_o}\right)^{d_{11}}\left(\frac{h_s}{D_c}\right)^{e_{11}}\left(\frac{t}{D_c}\right)^{g_{11}}\left(\frac{D_k}{D_c}\right)^{h_{11}}\right]^{n_{11}} \quad 3.12)$$

**Bed with blade promoter**

$$\frac{\Delta p_d}{\Delta p_b} = K_{12}\left[\left(G_{mrf}\right)^{a_{12}}\left(\frac{\rho_s}{\rho_f}\right)^{b_{12}}\left(\frac{A_{do}}{A_c}\right)^{c_{12}}\left(\frac{d_p}{d_o}\right)^{d_{12}}\left(\frac{h_s}{D_c}\right)^{e_{12}}\right]^{n_{12}} \tag{3.13}$$

The values of individual exponents (a to h) have been obtained using the log-log plots of respective dependent parameter ($R'$, $r'$ and $\frac{\Delta p_d}{\Delta p_b}$) against independent parameters for different beds and fitted to straight lines. For the final values of constants ($K$) and exponents (n), the correlation plots of respective dependent parameters ($R'$, $r'$ and $\frac{\Delta p_d}{\Delta p_b}$) against system parameters of different beds drawn seperately and fitted to straight lines have been used.

The final correlations and results, thus obtained for bed expansion, fluctuation and pressure drop ratios for different beds have been reported in chapters 4, 5 and 6 respectively.

### 3.3.2 Application of artificial neural network (ANN)

Computation through neural networks is one of the recently growing areas of artificial intelligence. Neural networks are promising due to their ability to learn highly nonlinear relationship. An artificial neural network based model has been defined in literature as a computing system made up of a number of simple, highly interconnected processing elements, which processes information by its dynamic state response to external inputs [3, 4]. The back propagation network which is the most well known and widely used among the current types of neural network system [5], has been used in the present study.

In the present case, a software package for artificial neural network developed by Rao & Rao [6] using back propagation algorithm has been used.

The different dependent and independent variables were normalized so as to lie in the same range group of 0-1. For proper training of the input-output data, the number of neurons in the hidden layer of the ANN structures (IXH XO) was decided on the basis of least error criterion. For this, tests were conducted for different ANN structures (IXHXO) for fixed epochs (cycles) and constant learning rate and other ANN-parameters viz. error tolerance, momentum parameter, noise factor, and slope parameter. In each test, the error obtained was noted and a structure with least error was selected for rigorous training of the system. The learning rate was varied in the range of 0.001-0.100 during the training of the input-output data. The number of cycles selected during training was high so that the ANN model could be rigorously trained.

The training of the network using input and output data for particular type of bed resulted in a system (model) which can be conveniently used as a tool for prediction of the output. In the present investigation several such models for different beds have been developed and their prediction have been used to compare with the results obtained through corresponding dimensional analysis.

The processing of data by the above two techniques (viz. dimensional analysis and ANN) have been adopted in chapters 4, 5 and 6. In addition the data have also been processed following analytical technique other than the above two in chapters 7 and 8.

## Nomenclature

| | |
|---|---|
| a,b,c,d,e,f,g,h | exponents |
| $A_c$ | area of column , $L^2$ |
| $A_{do}$ | open area of distributor, $L^2$ |
| ANN | artificial neural network |
| $A_o$ | open area in promoted bed with rod promoters, $L^2$ |
| $D_{1-5}$ | distributor |
| $D_c$ | column diameter , L |
| $D_e$ | equivalent diameter of promoter, $4A_o / P$ , L |
| $D_k$ | disk diameter, L |
| $d_o$ | orifice diameter , L |
| $d_{p\ 1-5}$ | particle size, L |
| $G_f$ | fluidization mass velocity, $ML^{-2}T^{-1}$ |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted beds, $ML^{-2}T^{-1}$ |
| $G'_{mf}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $G_{mrf}$ | reduced fluidization mass velocity for unpromoted beds, $G_f / G_{mf}$ |
| | reduced fluidization mass velocity for promoted beds, $G_f / G'_{mf}$ |
| $G_R$ | mass velocity ratio for unpromoted beds, $\left(G_f - G_{mf}\right)/\left(G_t - G_{mf}\right)$ |
| | mass velocity ratio for promoted beds, $\left(G_f - G'_{mf}\right)/\left(G_t - G'_{mf}\right)$ |

| | |
|---|---|
| $G_t$ | terminal mass velocity, $ML^{-2}T^{-1}$ |
| H | Hidden nodes |
| $h_{av}$ | average height of fluidized bed, $(h_{\max} + h_{\min})/2$, L |
| $h_{\max}$ | maximum height of fluidized bed, L |
| $h_{\min}$ | minimum height of fluidized bed, L |
| $h_{s\ 1\text{-}4}$ | initial static bed height, L |
| I | input nodes |
| $K_{1\text{-}12}$ | constants |
| $M_{1\text{-}4}$ | bed materials |
| $n_{1\text{-}12}$ | final exponents |
| O | output nodes |
| $P$ | total rod perimeter, L |
| $P_{1-12}$ | promoters |
| $r$ | bed fluctuation ratio, $h_{\max}/h_{\min}$ |
| $r'$ | modified bed fluctuation ratio, $r-1$ |
| $R$ | bed expansion ratio, $h_{av}/h_s$ |
| $R'$ | modified bed expansion ratio, $R-1$ |
| $t$ | thickness of the disk plate, L |
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |

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**Table 3.1** Scope of experiments

**Table 3.1.1** Distributor characteristics

| Distributor | Number of orifice | Diameter of orifice, $d_o$ (mm) |
|---|---|---|
| $D_1$ | 37 | 3.00 |
| $D_2$ | 37 | 2.50 |
| $D_3$ | 37 | 2.00 |
| $D_4$ | 37 | 1.50 |
| $D_5$ | 37 | 1.00 |

**Table 3.1.2** Promoter characteristics

| Promoter specification | | Disk diameter, $D_k$ x10$^3$ (m) | Disk thickness, $t$ x 10$^3$ (m) | No. of 4 mm diameter longitudinal rod |
|---|---|---|---|---|
| Rod: | $P_1$ | — | — | 4 |
| | $P_2$ | — | — | 8 |
| | $P_3$ | — | — | 12 |
| | $P_4$ | — | — | 16 |
| Disk | $P_5$ | 28.000 | 3.18 | — |
| | $P_6$ | 28.000 | 6.36 | — |
| | $P_7$ | 28.000 | 9.54 | — |
| | $P_8$ | 28.000 | 12.72 | — |
| | $P_9$ | 20.260 | 6.36 | — |
| | $P_{10}$ | 34.000 | 6.36 | — |
| | $P_{11}$ | 39.125 | 6.36 | — |
| Blade: | $P_{12}$ | 38.000 | 6.36 | — |

**Table 3.1.3** Bed Characteristics

| **A. Properties of bed material** | | | |
|---|---|---|---|
| Materials | $d_p$ x$10^3$,m | $\rho_s$ x$10^{-3}$,kg/m$^3$ | sphericity($\phi_s$) |
| Alum ($M_1$) | 0.725 ($d_{p4}$) | 1.69 | 0.7050 |
| Dolomite($M_2$) | 0.328 ($d_{p1}$) | 2.82 | 0.9452 |
| Dolomite($M_2$) | 0.390 ($d_{p2}$) | 2.82 | 0.9108 |
| Dolomite($M_2$) | 0.463 ($d_{p3}$) | 2.82 | 0.8715 |
| Dolomite($M_2$) | 0.725 ($d_{p4}$) | 2.82 | 0.7679 |
| Dolomite($M_2$) | 1.125 ($d_{p5}$) | 2.82 | 0.6319 |
| Fe-Ore($M_3$) | 0.725 ($d_{p4}$) | 3.90 | 0.6929 |
| Mn-Ore($M_4$) | 0.725 ($d_{p4}$) | 4.88 | 0.7261 |

| **B. Bed parameter** | | | | |
|---|---|---|---|---|
| Initial static bed height, $h_s$ x $10^2$, m | 8 ($h_{s1}$) | 12 ($h_{s2}$) | 16 ($h_{s3}$) | 20 ($h_{s4}$) |

| **C: Fluid properties** | | | | |
|---|---|---|---|---|
| Fluids | Average Temp.,$^o$c | Density at NTP, kg/m$^3$ | Viscosity Pa-s | Uses |
| Air | 20 | 1.2 | 1.81x$10^{-5}$ | Fluidizing medium |
| Carbon tetrachloride | 20 | 1588 | ____ | Manometric liquid |

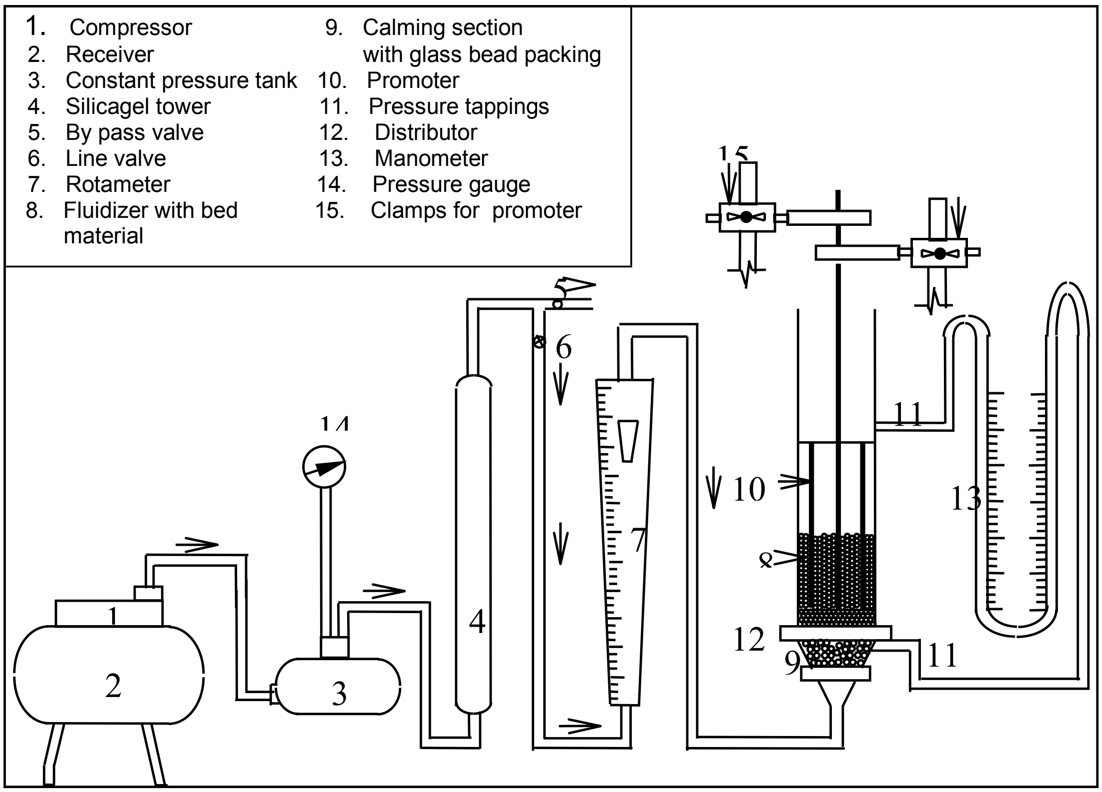
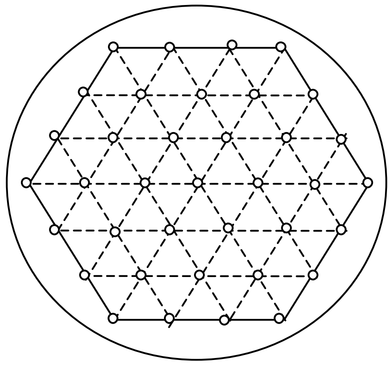
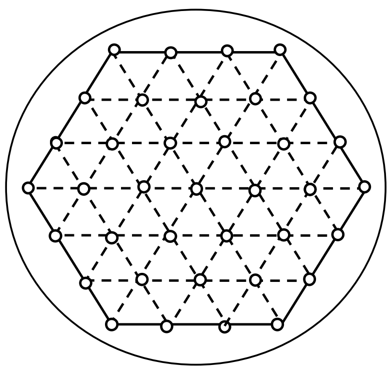
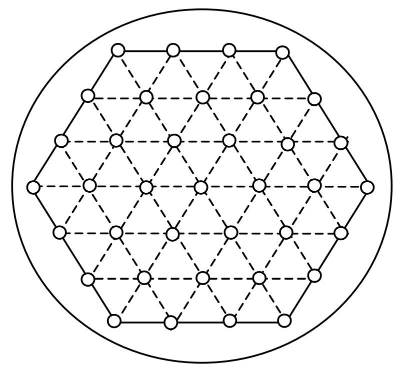



**Fig.3.1** Experimental setup



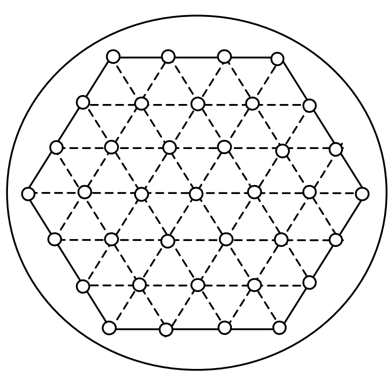
**Distributor: $D_1$**
**Diameter of orifices: 1.0 mm**
**No. of orifices: 37; Pitch: 7.5 mm**

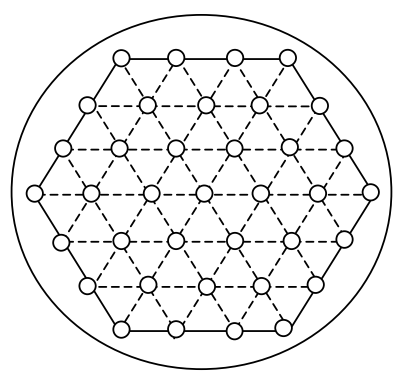




**Distributor: $D_2$**
**Diameter of orifices: 1.5 mm**
**No. of orifices: 37; Pitch: 7.5 mm**

**Distributor: $D_3$**
**Diameter of orifices: 2.0 mm**
**No. of orifices: 37; Pitch: 7.5 mm**

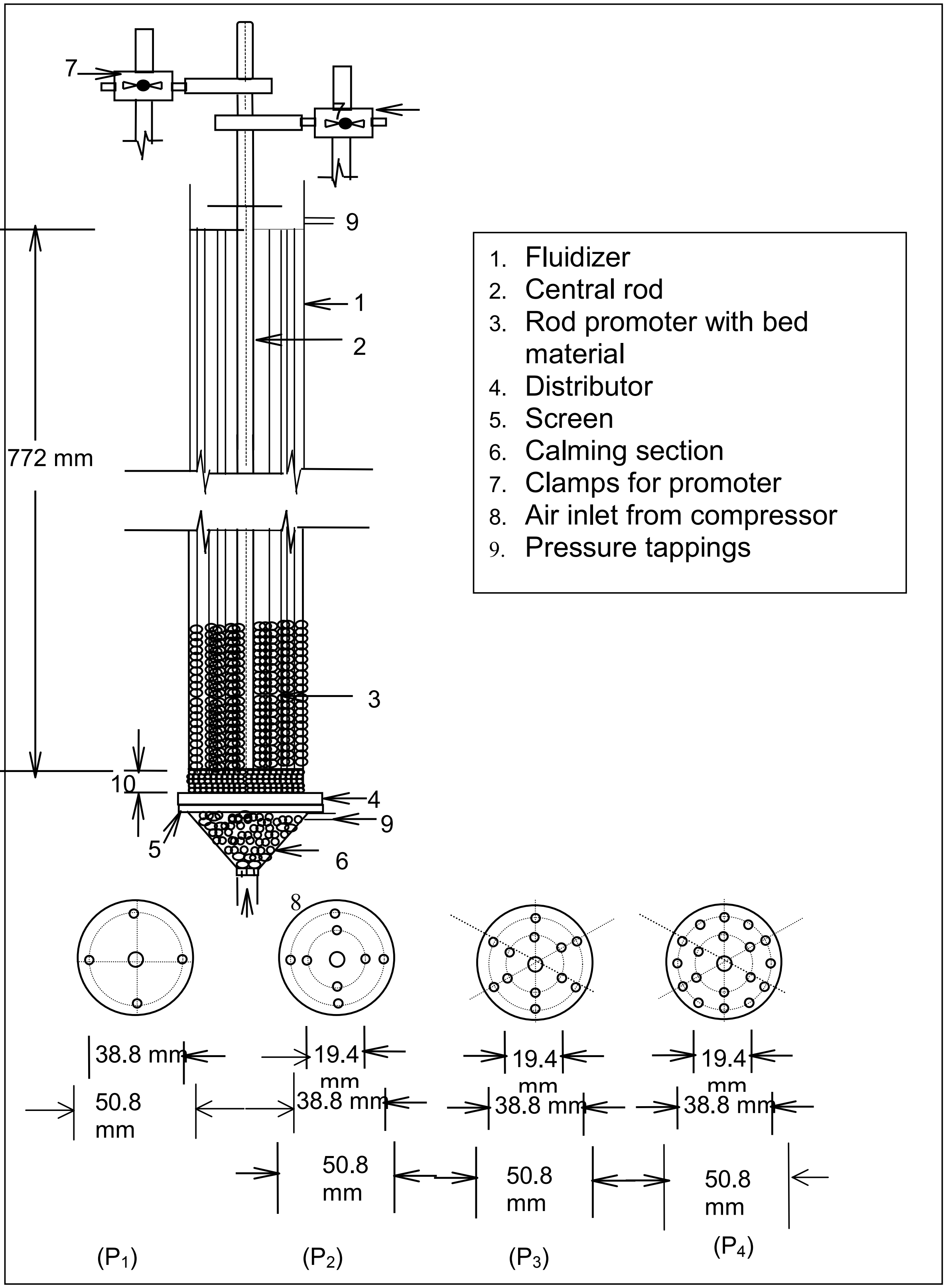




**Distributor: $D_4$**
**Diameter of orifices: 2.5 mm**
**No. of orifices: 37; Pitch: 7.5 mm**

**Distributor: $D_5$**
**Diameter of orifices: 3.0 mm**
**No. of orifices: 37; Pitch: 7.5 mm**

**Fig. 3.2** Details of distributors ($D_1$ - $D_5$)


7
7
9
1
2
3
772 mm
10
4
9
5
6
8
1. Fluidizer
2. Central rod
3. Rod promoter with bed material
4. Distributor
5. Screen
6. Calming section
7. Clamps for promoter
8. Air inlet from compressor
9. Pressure tappings
38.8 mm
50.8 mm
19.4 mm
38.8 mm
50.8 mm
19.4 mm
38.8 mm
50.8 mm
19.4 mm
38.8 mm
50.8 mm
(P1)
(P2)
(P3)
(P4)

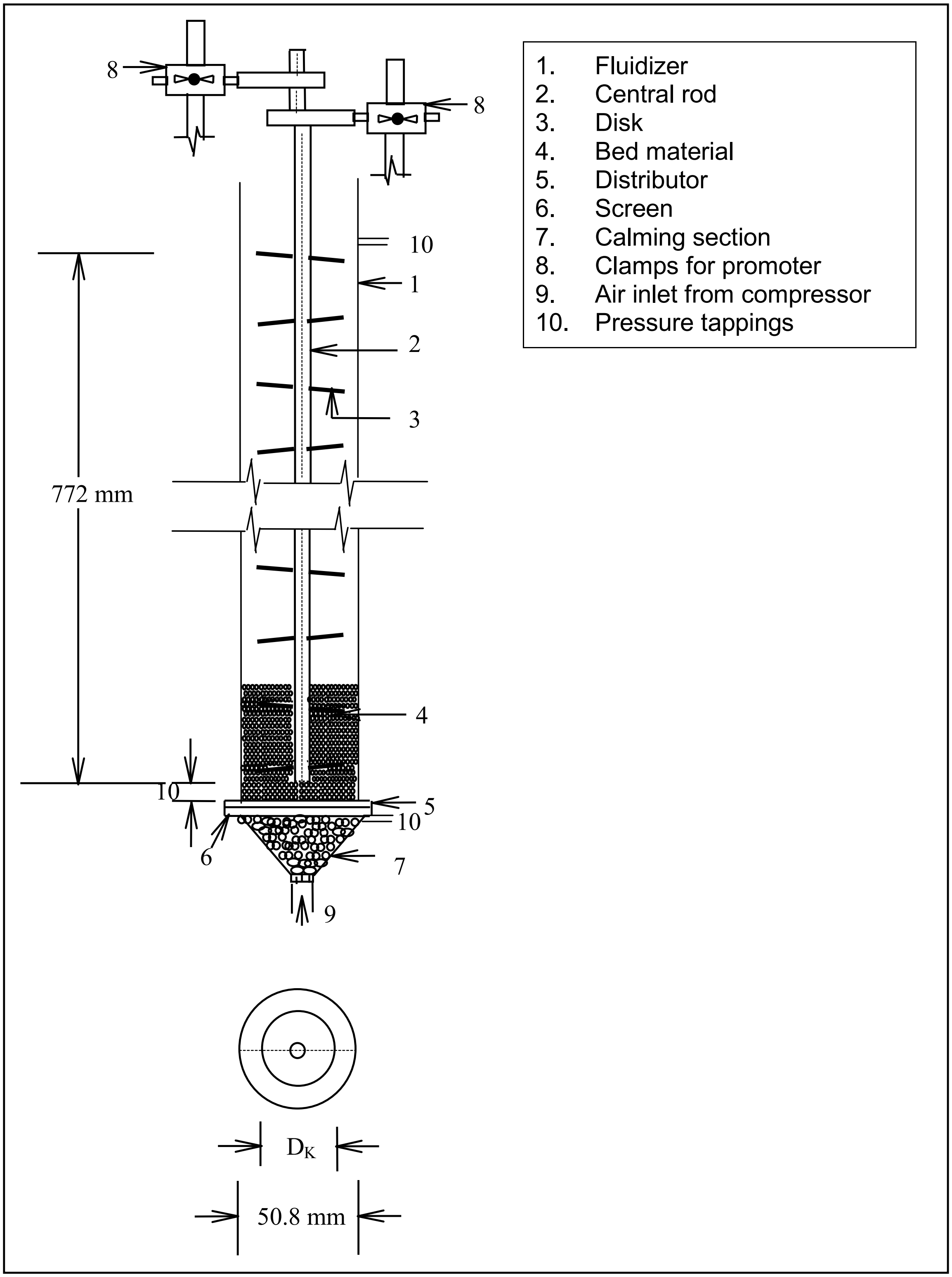



**Fig. 3.4** Details of promoted bed using disk promoter

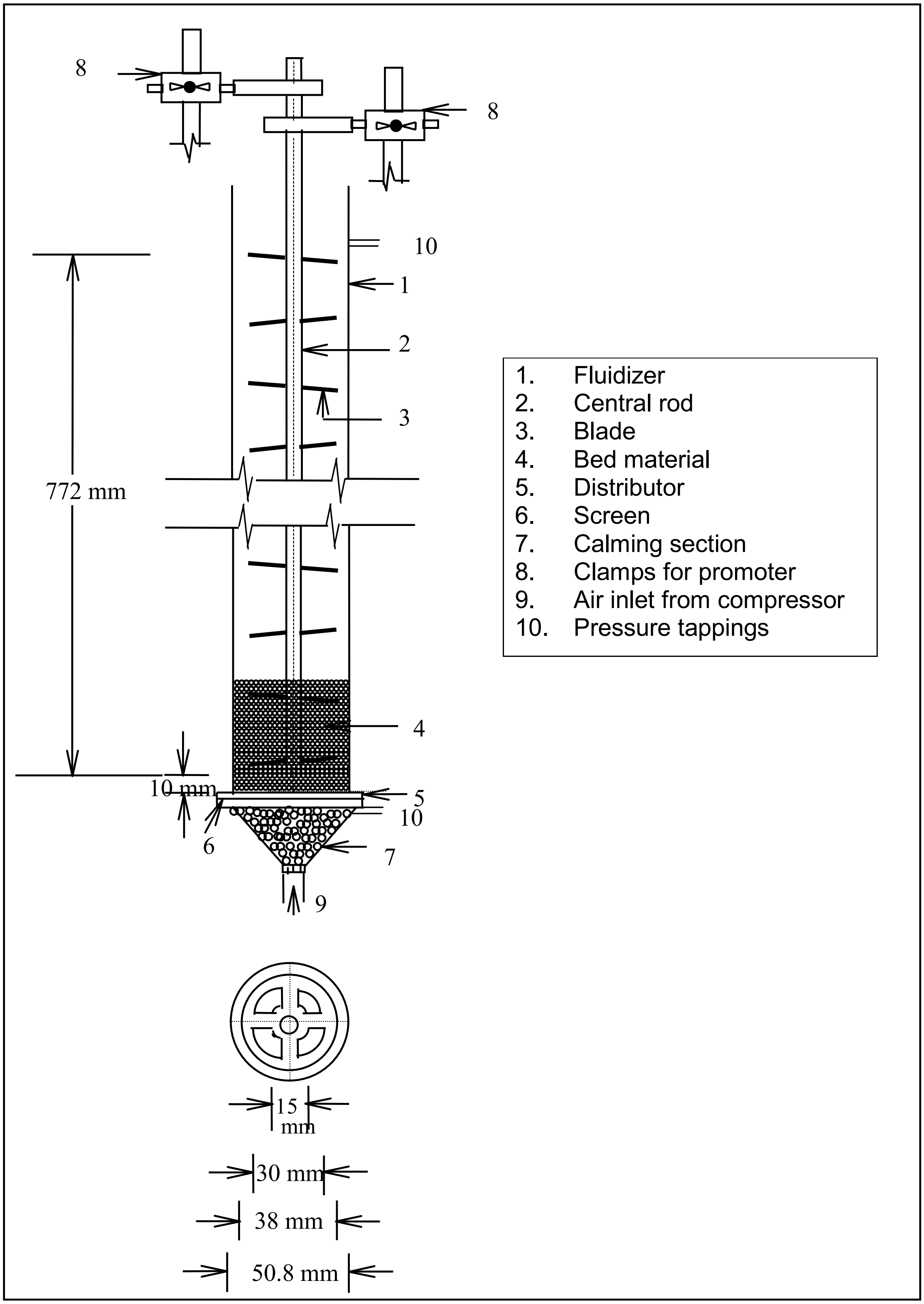



**Fig. 3.5** Details of promoted bed using blade promoter

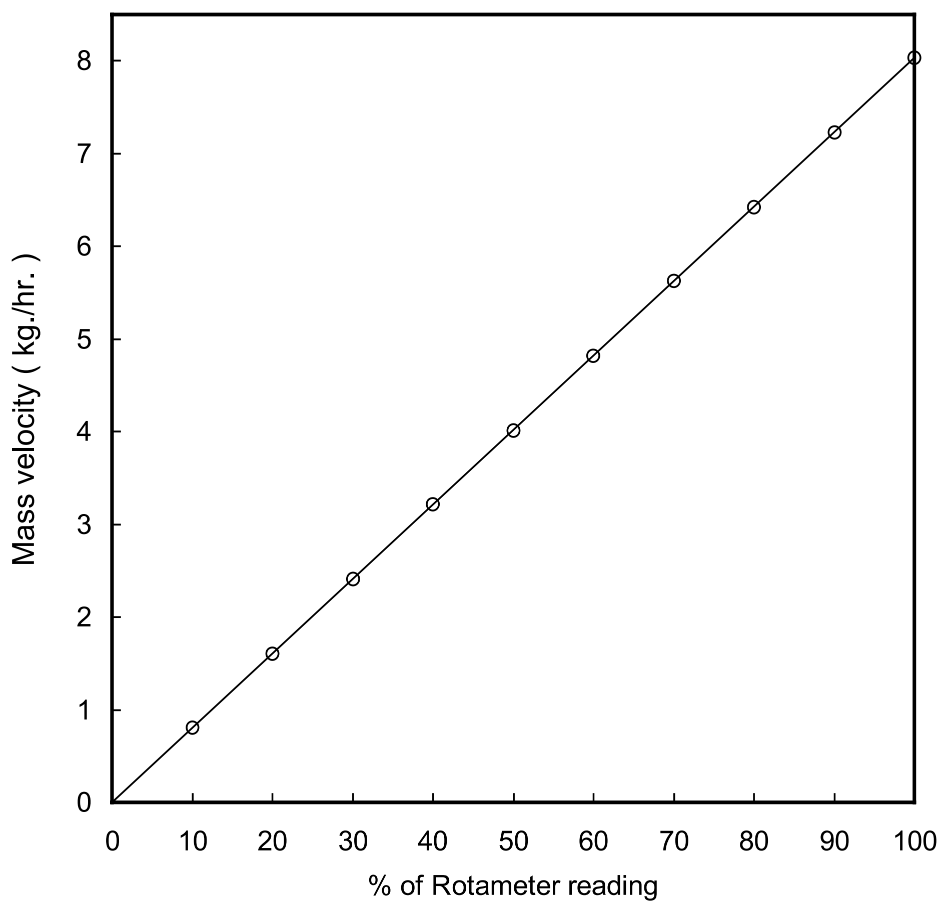



**Fig. 3.6** calibration of lower range rotameter

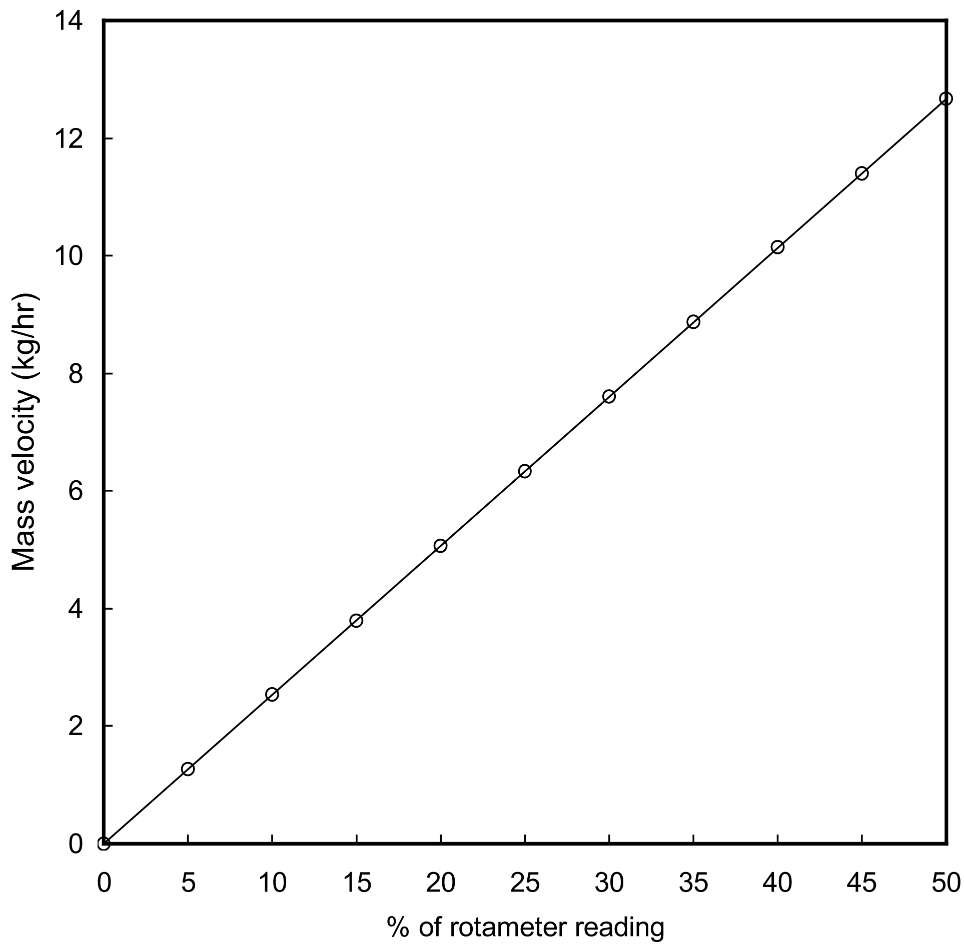



**Fig. 3.7** calibration of higher range rotameter

**Plate 3.1** Experimental setup

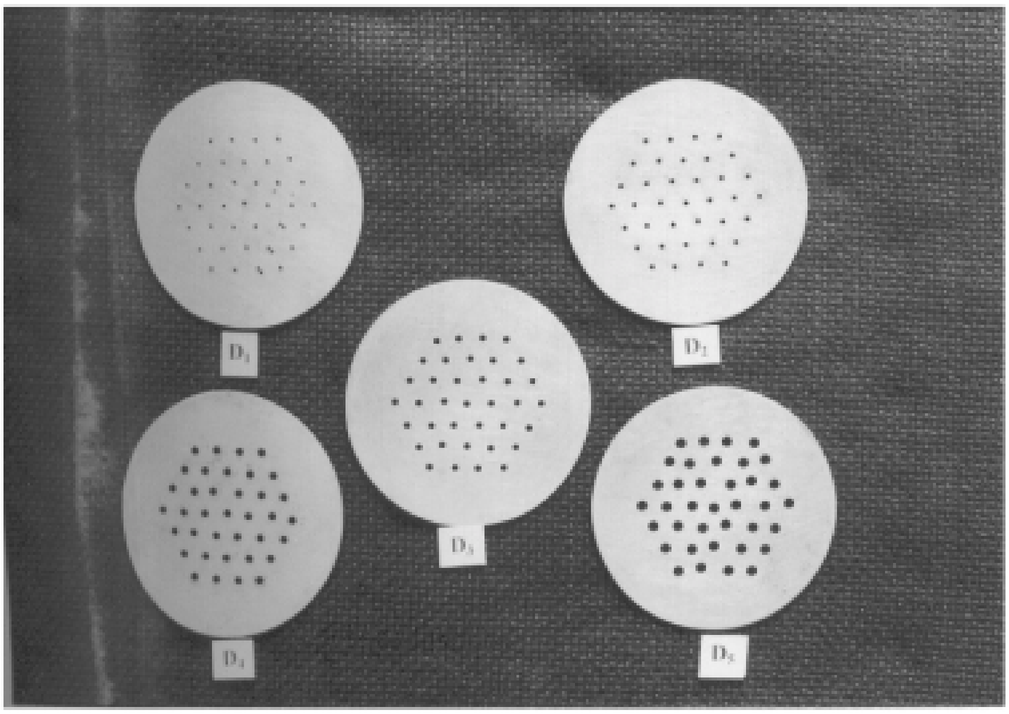
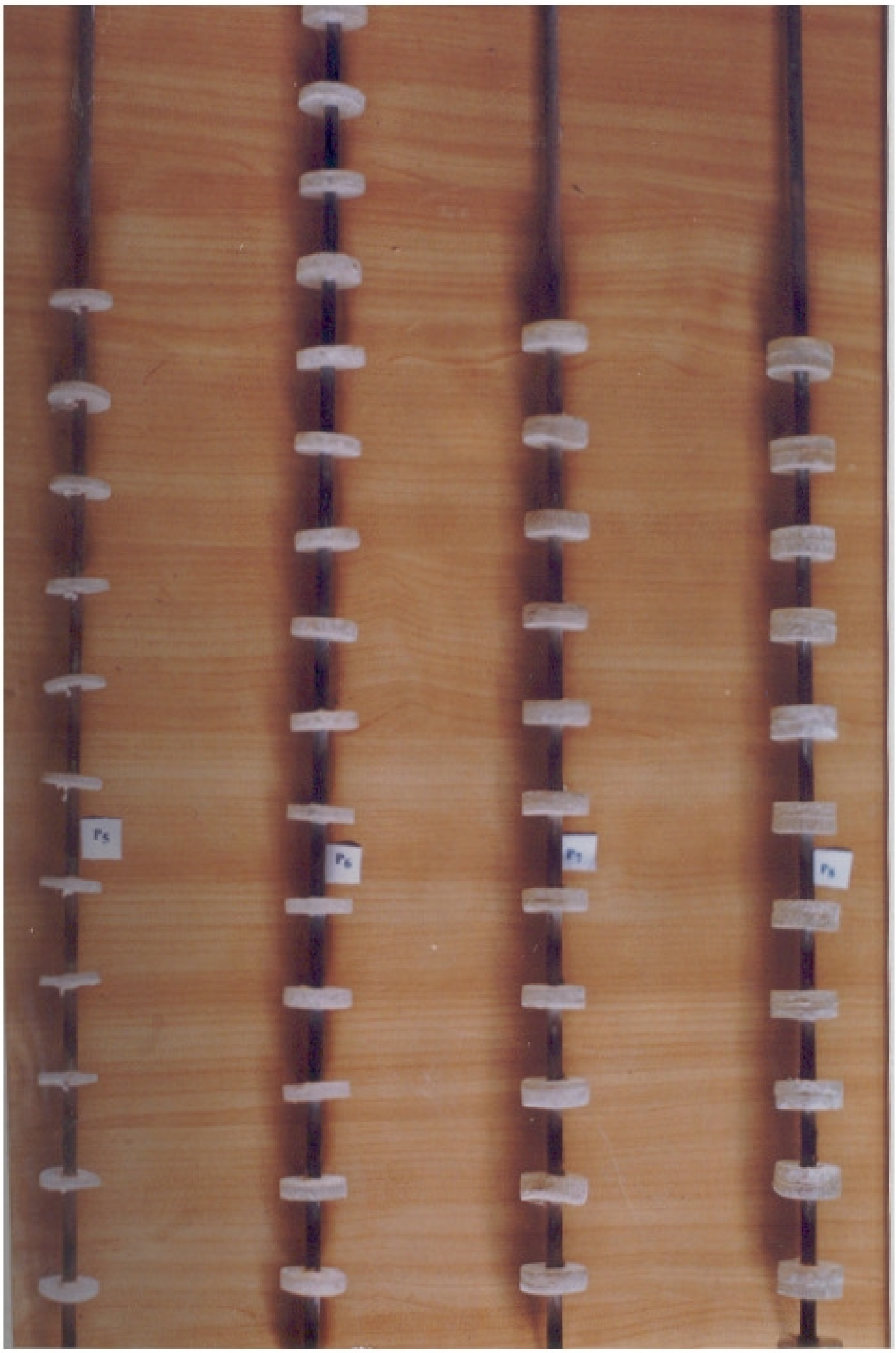


**Plate 3.2** Details of distributors

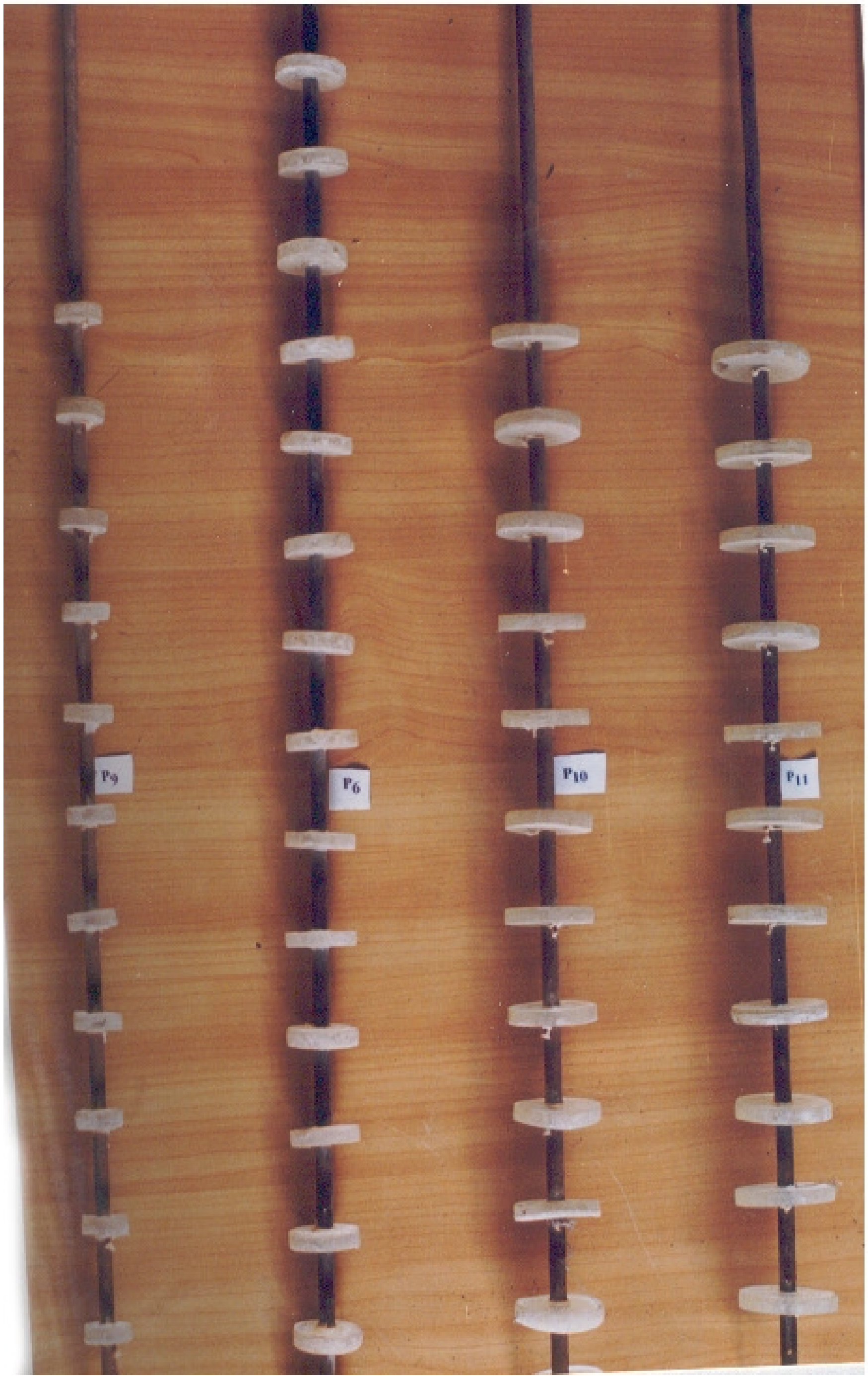
$P_1$ $P_2$ $P_3$ $P_4$

**Plate 3.3** Details of rod promoter



$P_5$ $P_6$ $P_7$ $P_8$

**Plate 3.4** Details of disk promoter (varying disk thickness)




$P_9$ $P_6$ $P_{10}$ $P_{11}$

**Plate 3.5** Details of disk promoter (varying disk diameter)

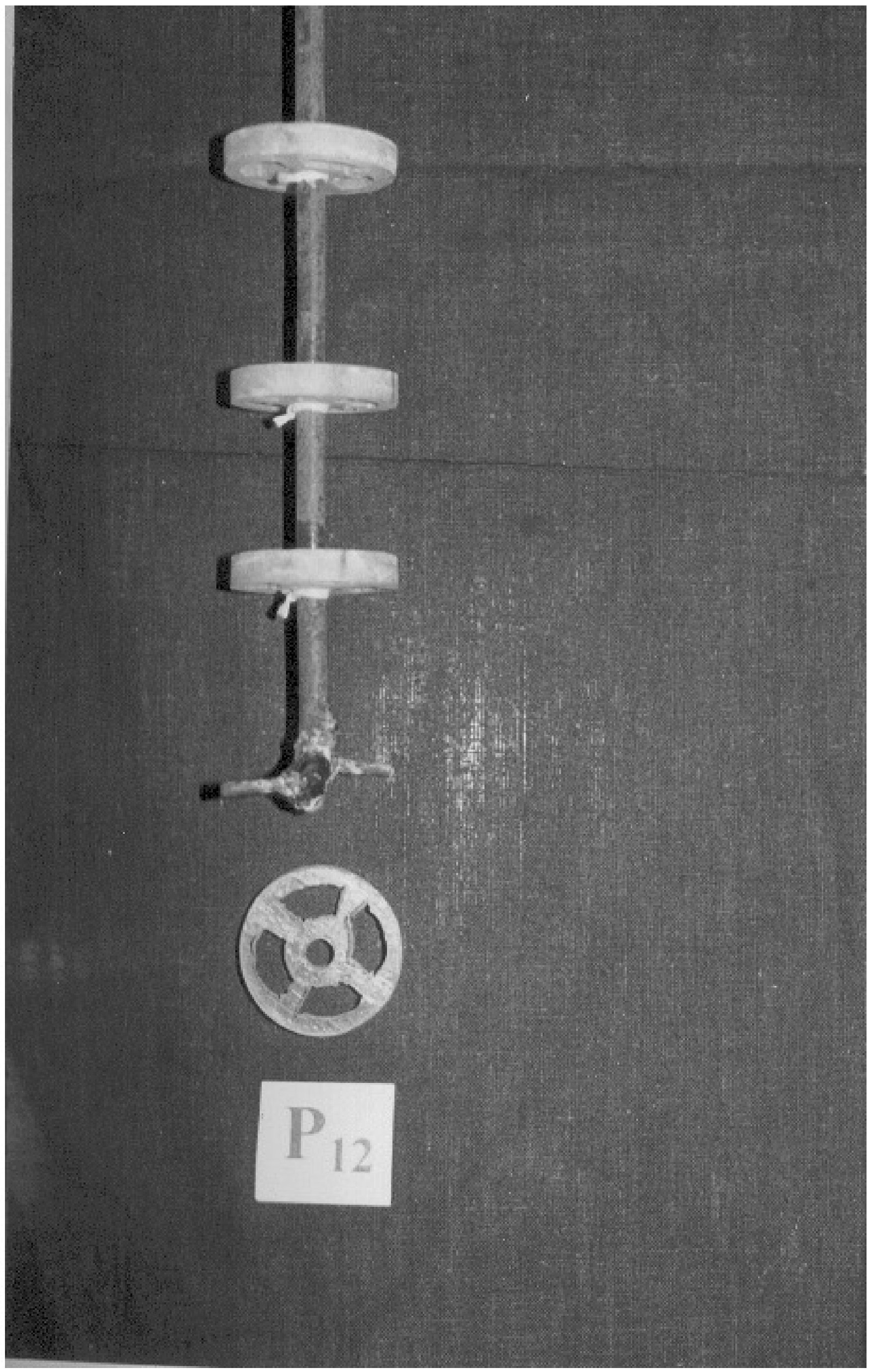



**Plate 3.6** Details of blade promoter

# CHAPTER IV
# Prediction of bed expansion ratio

## 4.1 Introduction

A bed of solid particles behaves as a fixed bed at low flow rate at upward low rate of fluid through it, but if the flow rate is sufficiently large, the particles will be freely suspended in the fluid to give rise to a fluidized bed. The fluidization of solid particles differ greatly depending on (a) the nature of the solids, (b) the nature of the fluid and its flow pattern and (c) nature of the bed (unpromoted or promoted).

Based on the nature of fluidization, the classification is as follows:
(a) dense phase, (b) lean phase, (c) particulate and (d) aggregative. Wilhem and Kwauk [1] are the first to use the terms 'particulate' and 'aggregative'. They have suggested Froude number $\left(U_{mf}^{2} / d_{p}g\right)$ as a criterion for the nature of fluidization. Partculate fluidization is characterised as a state in which the particles are discretely separated from each other. Aggregative fluidization is a state of fluidization wherein the particles are present in the bed not as individual ones, but rather as aggregates.

In aggregative fluidization, the gas rises through the bed primarily in the form of bubbles. Within these bubbles there may be entrained solids. Hence an aggregatively fluidizing bed is a heterogeneous body, composed of two separate coexisting phases.

For Froude number in the order of unity, particulate state of fluidization is observed, either for liquid-solid system with very dense solid or for gas-solid system with fine and light particles. Dense gas under pressure also offers particulate behaviour over a large range of flow rates.

Between minimum fluidization and minimum bubbling velocity, a fluidized bed of fine powders can exhibit particulate expansion to a large extent.

An early analysis of particulate expansion is by Godard and Richardson as reported by Richardson [2]. In solid-liquid system, the velocity-voidage variation for gas-solid system can be represented by straight lines in a logarithmic plot. Hence following a Richardson and Zaki equation [3], Dejong and Nomden [4], Simone and Harriott [5] and Abrahamsen and Geldart [6] demonstrated that plotting $\varepsilon^3/(1-\varepsilon)$ against the gas velocity gives a straight line on a logarithmic plot. Abrahmsen and Geldart (loc. cit.) represented the expansion of non-bubbling beds of fine powder as:

$$\frac{\varepsilon^3}{1-\varepsilon}\frac{(\rho_s-\rho_f)g{d_p}^2}{\mu_f}=210(u-u_{mf})+\frac{{\varepsilon_{mf}}^3}{1-\varepsilon_{mf}}\frac{(\rho_s-\rho_f)g{d_p}^2}{\mu_f} \tag{4.1}$$

Mustsers and Rietema [7] suggested that interparticle forces play an important role in the particulate behaviour of fine powders.

Gas-solid fluidized bed, generally of aggregative nature, is marked by occurance of bubbles of varied sizes culminating in slugs. This results in non-uniform bed expansion and a poor fluidization phenomenon. Keeping in view the a-fore-said inherent drawbacks, bed with promoter (internal/baffle) can be employed in gas-solid fluidization with a view to smoothen the bed expansion behaviour and improve upon the fluidization quality.

Bed expansion ratio $(R)$ is defined as the ratio of the average height of a fluidized bed to initial static bed height at a particular flow rate of the fluidizing medium above the minimum fluidizing velocity. It is an important parameter for fixing the height of a fluidized bed required for a particular service.

The expansion ratio of a gas-solid fluidized bed depends on excess gas velocity ($G_f-G_{mf}$), particle size ($d_p$) and initial static bed height ($h_s$). Bed expansion is substantially greater in a two-dimensional bed than in a three-dimensional one. The bed expansion reported by different investigators have different meanings because of varied methods of measurement adopted. A number of investigations [3, 5, 6, 8, 9, 10] have been made with respect to the prediction of bed expansion in unpromoted beds. For promoted gas-solid fluidized beds, although considerable qualitative work [11-17] have been reported on the dynamic aspects such as improvement in bed homogeneity, bubble phenomenon, particle motion, fluid-solid mixing, pressure drop, minimum fluidization velocity etc. a very limited quantitative information is available on the improvement of fluidization quality in terms of bed expansion.

In the present work, the combined effect of promoter and distributor on bed expansion has been investigated. Four types of rod promoters, seven types of disk promoters along with one blade promoter have been used in beds supported on five distributors of varying open area (Table 3.1), and the data have been synthesized in terms of correlations from dimensional analysis approach and artificial neural network models. The results obtained using correlations, developed through dimensional analysis approach have also been supported by the prediction obtained by artificial neural network models.

## 4.2 Development of correlations

Bed expansion ratio is a function of static and dynamic properties of the fluidized bed. The relation can be expressed as functions of dimensionless groups containing bed, distributor and promoter parameters and the properties of the fluidized particles and the medium as:

$$R' = \phi\left( G_R, \frac{\rho_s}{\rho_f}, \frac{A_{do}}{A_c}, \frac{d_p}{d_o}, \frac{h_s}{D_c}, \frac{D_e}{D_c}, \frac{t}{D_c}, \frac{D_k}{D_c} \right) \tag{4.2}$$

or,

$$R' = \mathrm{K}\left(G_R\right)^a \left(\frac{\rho_s}{\rho_f}\right)^b \left(\frac{A_{do}}{A_c}\right)^c \left(\frac{d_p}{d_o}\right)^d \left(\frac{h_s}{D_c}\right)^e \left(\frac{D_e}{D_c}\right)^f \left(\frac{t}{D_c}\right)^g \left(\frac{D_k}{D_c}\right)^h \tag{4.3}$$

These correlations have been expressed in the form of modified bed expansion ratio $\left(R-1\right)$ in order to ensure boundary condition of zero expansion against zero excessive velocity i.e. at the onset of fluidization.

Analyzing the experimental data for the effect of the individual dimensionless group, the values of constant and the exponent have been obtained by the regression analysis of the data for respective beds. Using correlation plots (Figs. 4.1 to 4.4), the final expressions for modified bed expansion ratio for the unpromoted and the promoted beds with rod, disk and blade type promoters have been obtained as under:

**Unpromoted bed**

$$R' = 0.37\left(G_R\right)^{0.85}\left(\frac{\rho_s}{\rho_f}\right)^{0.59}\left(\frac{A_{do}}{A_c}\right)^{0.20}\left(\frac{d_p}{d_o}\right)^{0.41}\left(\frac{h_s}{D_c}\right)^{-0.32} \tag{4.4}$$

**Bed with rod promoter**

$$R' = 0.18\left(G_R\right)^{0.74}\left(\frac{\rho_s}{\rho_f}\right)^{0.56}\left(\frac{A_{do}}{A_c}\right)^{0.19}\left(\frac{d_p}{d_o}\right)^{0.29}\left(\frac{h_s}{D_c}\right)^{-0.40}\left(\frac{D_e}{D_c}\right)^{0.23} \tag{4.5}$$

**Bed with disk promoter**

$$R' = 0.08\left(G_R\right)^{0.75}\left(\frac{\rho_s}{\rho_f}\right)^{0.56}\left(\frac{A_{do}}{A_c}\right)^{0.19}\left(\frac{d_p}{d_o}\right)^{0.26}$$

$$\mathrm{X}\left(\frac{h_s}{D_c}\right)^{-0.47}\left(\frac{t}{D_c}\right)^{-0.24}\left(\frac{D_k}{D_c}\right)^{-0.48} \tag{4.6}$$

**Bed with blade promoter**

$$R' = 0.24\left(G_R\right)^{0.73}\left(\frac{\rho_s}{\rho_f}\right)^{0.51}\left(\frac{A_{do}}{A_c}\right)^{0.17}\left(\frac{d_p}{d_o}\right)^{0.22}\left(\frac{h_s}{D_c}\right)^{-0.71} \tag{4.7}$$

### 4.2.1 Development and use of artificial neural network models

Artificial neural network (ANN) based models have been developed to predict bed expansion ratio for the corresponding beds and to support and authenticate the results predicted by correlations developed from dimensional analysis approach. Four different ANN models using back propagation algorithm: one each for unpromoted bed and beds promoted with rod, disk and blade type of promoters have been developed. In each case, different ANN structures (I X H X O) with varying number of neurons in the hidden layer have been tested at constant epochs (cycles), learning rate, error tolerance, momentum parameter, noise factor, and slope parameter. Based on least error criterion (Tables 4.1-4.4 and 4.5) for respective beds, a system was selected for training of the input-output data. The learning rate was varied in the range of 0.001-0.100 during the training of the input-output data. The number of cycles selected during training was high so that the ANN models could be rigorously trained. The training of the network using input and output data for particular type of bed resulted in a system (model) which has been used as a tool for prediction of the bed expansion ratio for the corresponding bed. The comparison between predicted values of bed expansion ratio using ANN-models and the corresponding experimental ones (Tables 4.6 to 4.9) show that all the four ANN-models for different beds have been trained to a satisfactory level. Further, the values of the co-efficient of determination $\left(R^2\right)$ for training and testing data in case of unpromoted bed and beds promoted with rod, disk and blade promoters obtained respectively as (0.9853, 0.9789), (0.9877, 0.9761), (0.9854, 0.9826) and (0.9662, 0.9560), support the above claim.

## 4.3 Results and discussion

The comparative variation of bed expansion ratio $(R)$ with non- dimensional system parameter for different beds have been shown in Figs. 4.5 to 4.9 and with rod and disk promoter parameters in Figs. 4.10 to 4.12 under identical operating conditions. The values of bed expansion ratio calculated with the help of developed correlations: Eqs. 4.4 to 4.7 respectively for unpromoted bed and beds with rod, disk and blade promoters have been compared with the corresponding experimental ones and those predicted from ANN-models (Tables 4.6 to 4.9 for randomized data). From the comparison Tables 4.6-4.9, the predicted results using developed correlations have been found to be in good agreement with the corresponding experimental ones and those predicted by ANN-models. The mean and standard deviation of the experimental values from the calculated ones (using the above two methods) for bed expansion ratio in case of unpromoted and promoted beds with rod, disk and blade promoters have been given in Table 4.10.

Further, it can be observed that the developed correlations using dimensional analysis approach as well as ANN-models can be satisfactorily used for the prediction for bed expansion ratio in the respective beds. From the Table 4.10, it has been found that the prediction using ANN-models provide better prediction with reduced standard and mean deviation. But an ANN-model is only a system which can not be represented by the physical correlations. On the other hand, dimensional analysis method provide satisfactory predictions as well as correlations which show inter-relation between the dependent and independent variables of the system, and hence can be used more coveniently.

It is evident from the developed correlations that the bed expansion is significantly influenced by the distributor and promoter parameters in addition to other system parameters. As observed the reduction in bed expansion in case of the promoted beds over the unpromoted one can be attributed to the breaking up of bubbles and controlling their size and growth. The radial promoter elements facilitate smooth fluidization with negligible channelling and slugging compared to the unpromoted bed and the beds with rod type promoter. The reduction of bed expansion with the increase in blockage volume by the promoters in terms of larger number of rods in the case of rod promoter and the increase in disk diameter/thickness for the disk promoter is due to the increase in the effectiveness of the promoter elements in breaking bubbles and minimizing slugging (Table 4.11, Sl. No.23 to 25, column no. 5 and 8 for rod promoter and Sl. No. 23-28, column no. 6 and 9 for disk promoter).

Further, the reduction of bed expansion with the decrease of the distributor open area may be due to the formation of bubbles of smaller sizes generated from orifices of smaller diameter and better distribution of the fluidizing medium.

## 4.4 Conclusions

For identical operating parameters, the bed expansion increases with an increase in gas velocity (Fig. 4.5). In addition, the bed expansion is significantly influenced by the distributor and promoter parameters and other system variables (Table 4.11). The comparison of the calculated results (Table 4.11) for the bed expansion ratio for the unpromoted beds and beds with rod, disk and blade promoters shows that all types of promoters used in the investigation are quite effective in reducing the bed expansion over the unpromoted ones. Further, it has been observed that the disk and blade type promoters are more effective (with blade type being better in performance) in reducing bed expansion when compared with beds having rod type promoters and the unpromoted ones. Also, the decrease of the distributor open area results in the reduction of bed expansion. The reduction in bed expansion for both the above parameters viz., the promoters and the distributors are evident for almost the complete regime of fluidization except in the neighbourhood of the minimum fluidization condition (i.e.$G_R \leq 0.015$) where the bed dynamics was not fully stabilized.

Thus, the combined effect of an appropriate promoter and a distributor with decreased open area results in better quality gas-solid fluidization with reduced bubble formation and slugging, limiting thereby the size of the bed with appreciable reduction of transport dis-engaging height (TDH )

## Nomenclature

| | |
|---|---|
| $a, b, c, d, e, f, g, h$ | exponents |
| $A_c$ | cross sectional area of column, $L^2$ |
| $A_{do}$ | open area of distributor, $L^2$ |
| $A_o$ | open area in promoted bed with rod promoter, $L^2$ |
| BP | bed with blade type of promoter |
| $D_c$ | column diameter, L |
| $D_e$ | equivalent diameter of promoter, $4A_o / P$, L |
| $D_k$ | disk diameter, L |
| DP | bed with disk promoter |
| $d_o$ | orifice diameter , L |

| | |
|---|---|
| $d_p$ | particle size, L |
| $G_f$ | fluidization mass velocity, $ML^{-2}T^{-1}$ |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted beds, $ML^{-2}T^{-1}$ |
| $G'_{mf}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $G_R$ | mass velocity ratio for unpromoted beds, $\left(G_f - G_{mf}\right)/\left(G_t - G_{mf}\right)$ |
| | mass velocity ratio for promoted beds, $\left(G_f - G'_{mf}\right)/\left(G_t - G'_{mf}\right)$ |
| $G_t$ | terminal mass velocity, $ML^{-2}T^{-1}$ |
| $h_{av}$ | average bed height, $\left(h_{\max} + h_{\min}\right)/2$, L |
| $h_{\max}$ | maximum height of fluidized bed, L |
| $h_{\min}$ | minimum height of fluidized bed, L |
| $h_s$ | initial static bed height, L |
| K | constant |
| $P$ | total rod perimeter, L |
| $R$ | bed expansion ratio, $h_{av} / h_s$ |
| $R'$ | modified bed expansion ratio, $R-1$ |
| $R^2$ | coefficient of determination |
| RP | bed with rod promoter |
| $t$ | thickness of the disk plate, L |
| UP | unpromoted bed |
| $u$ | superficial fluid velocity (measured in empty column), $LT^{-1}$ |
| $u_{mf}$ | superficial fluid velocity at minimum fluidization, $LT^{-1}$ |

*Greek letters*

| | |
|---|---|
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |
| $\mu_f$ | viscosity of fluid, $ML^{-1}T^{-1}$ |
| $\varepsilon$ | bed voidage |
| $\varepsilon_{mf}$ | bed voidage at minimum fluidization |

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**Table 4.1** Sum squared error (SSE) for various ANN structure tested for unpromoted bed

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H x O ) | Sum squared error |
| 5 2 1 | 0.097137 |
| 5 4 1 | 0.095418 |
| 5 6 1 | 0.094508 |
| 5 8 1 | 0.094933 |
| 5 9 1 | 0.089781 |
| 5 11 1 | 0.093871 |
| 5 13 1 | 0.094959 |
| 5 14 1 | 0.090062 |
| 5 16 1 | 0.091647 |
| 5 18 1 | 0.089672 |
| 5 20 1 | 0.091683 |
| 5 22 1 | 0.088497 |
| 5 23 1* | 0.086233 |
| 5 24 1 | 0.088599 |
| 5 25 1 | 0.092101 |

* selected structure

**Table 4.2** Sum squared error (SSE) for various ANN structure tested for bed with rod promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H x O ) | Sum squared error |
| 6 2 1 | 0.061607 |
| 6 4 1 | 0.059663 |
| 6 6 1 | 0.060907 |
| 6 7 1 | 0.058659 |
| 6 10 1 | 0.056633 |
| 6 12 1 | 0.058402 |
| 6 13 1 | 0.056075 |
| 6 14 1 | 0.058369 |
| 6 15 1 | 0.052242 |
| 6 16 1 * | 0.051434 |
| 6 17 1 | 0.054055 |
| 6 18 1 | 0.054782 |

* selected structure

**Table 4.3** Sum squared error (SSE) for various ANN structure tested for bed with disk promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H x O ) | Sum squared error |
| 7 2 1 | 0.049059 |
| 7 4 1 | 0.048937 |
| 7 6 1 | 0.043393 |
| 7 8 1 | 0.045415 |
| 7 9 1 | 0.045368 |
| 7 11 1 | 0.042703 |
| 7 14 1 | 0.04265 |
| 7 16 1 | 0.044373 |
| 7 18 1 | 0.040261 |
| 7 20 1 * | 0.038358 |
| 7 21 1 | 0.039666 |
| 7 22 1 | 0.042551 |

* selected structure

**Table 4.4** Sum squared error (SSE) for various ANN structure tested for bed with blade promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H X O ) | Sum squared error |
| 5 2 1 | 0.048788 |
| 5 4 1 | 0.046227 |
| 5 5 1 | 0.048346 |
| 5 6 1 | 0.043553 |
| 5 7 1 | 0.044163 |
| 5 9 1 | 0.046478 |
| 5 10 1 | 0.04581 |
| 5 12 1 | 0.045326 |
| 5 14 1 | 0.044128 |
| 5 15 1 | 0.041903 |
| 5 16 1 | 0.042812 |
| 5 17 1 | 0.041084 |
| 5 18 1 * | 0.037357 |
| 5 19 1 | 0.04119 |
| 5 20 1 | 0.041815 |
| 5 21 1 | 0.040529 |

* selected structure

**Table 4.5** Selected structures of neural network models for test problems undertaken

| Learning rate 0.001-0.100 | | | | |
|---|---|---|---|---|
| Bed particulars | Input Nodes | Hidden Nodes | Output Nodes | Number of cycles used for training |
| Unpromoted bed | 5 | 23 | 1 | 50,000 |
| Bed with rod promoter | 6 | 16 | 1 | 50,000 |
| Bed with disk promoter | 7 | 21 | 1 | 50,000 |
| Bed with blade promoter | 5 | 18 | 1 | 50,000 |

**Table 4.6** Comparison between experimental and calculated (Eq. 4.4 and ANN-models) values of bed expansion ratio for unpromoted bed

| Serial No. | System variables | | | | | Bed expansion ratio ( $R$ ) | | |
|---|---|---|---|---|---|---|---|---|
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | Exptl. | Predicted by | |
| | | | | | | | Eq. 4.4 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 0.051 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.88 | 1.81 | 1.79 |
| 2 | 0.107 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.55 | 2.52 | 2.59 |
| 3 | 0.109 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.68 | 2.55 | 2.63 |
| 4 | 0.126 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.95 | 2.76 | 2.84 |
| 5 | 0.150 | 3245.8 | 0.09 | 0.29 | 2.36 | 3.38 | 3.46 | 3.29 |
| 6 | 0.035 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.37 | 1.43 | 1.34 |
| 7 | 0.125 | 1409.2 | 0.09 | 0.29 | 2.36 | 2.10 | 2.29 | 2.18 |
| 8 | 0.151 | 1409.2 | 0.09 | 0.29 | 2.36 | 2.30 | 2.51 | 2.35 |
| 9 | 0.177 | 1409.2 | 0.09 | 0.29 | 2.36 | 2.5 | 2.73 | 2.49 |
| 10 | 0.045 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.88 | 1.88 | 1.8 |
| 11 | 0.070 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.19 | 2.29 | 2.18 |
| 12 | 0.087 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.31 | 2.54 | 2.43 |
| 13 | 0.104 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.78 | 2.80 | 2.70 |
| 14 | 0.120 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.89 | 3.03 | 2.91 |
| 15 | 0.020 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.53 | 1.51 | 1.70 |
| 16 | 0.035 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.84 | 1.81 | 1.89 |
| 17 | 0.049 | 4066.7 | 0.09 | 0.29 | 2.36 | 2.07 | 2.09 | 2.08 |
| 18 | 0.051 | 4066.7 | 0.09 | 0.29 | 2.36 | 2.16 | 2.13 | 2.11 |
| 19 | 0.078 | 4066.7 | 0.09 | 0.29 | 2.36 | 2.55 | 2.61 | 2.47 |
| 20 | 0.051 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.92 | 1.87 | 1.94 |
| 21 | 0.060 | 2347.5 | 0.129 | 0.29 | 2.36 | 2.08 | 2.01 | 2.09 |
| 22 | 0.126 | 2347.5 | 0.129 | 0.29 | 2.36 | 2.97 | 2.89 | 3.01 |
| 23 | 0.051 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.68 | 1.74 | 1.67 |
| 24 | 0.097 | 2347.5 | 0.057 | 0.29 | 2.36 | 2.30 | 2.28 | 2.32 |
| 25 | 0.107 | 2347.5 | 0.057 | 0.29 | 2.36 | 2.51 | 2.39 | 2.45 |
| 26 | 0.070 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.86 | 1.86 | 1.83 |
| 27 | 0.079 | 2347.5 | 0.032 | 0.29 | 2.36 | 2.02 | 1.96 | 1.96 |
| 28 | 0.088 | 2347.5 | 0.032 | 0.29 | 2.36 | 2.10 | 2.05 | 2.09 |

Continued on next page

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 29 | 0.107 | 2347.5 | 0.032 | 0.29 | 2.36 | 2.39 | 2.24 | 2.33 |
| 30 | 0.109 | 2347.5 | 0.032 | 0.29 | 2.36 | 2.45 | 2.26 | 2.36 |
| 31 | 0.126 | 2347.5 | 0.032 | 0.29 | 2.36 | 2.60 | 2.43 | 2.57 |
| 32 | 0.042 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.49 | 1.47 | 1.39 |
| 33 | 0.051 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.57 | 1.56 | 1.51 |
| 34 | 0.109 | 2347.5 | 0.014 | 0.29 | 2.36 | 2.20 | 2.07 | 2.28 |
| 35 | 0.034 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.61 | 1.69 | 1.70 |
| 36 | 0.083 | 2347.5 | 0.09 | 0.45 | 2.36 | 2.49 | 2.47 | 2.42 |
| 37 | 0.098 | 2347.5 | 0.09 | 0.45 | 2.36 | 2.61 | 2.69 | 2.65 |
| 38 | 0.113 | 2347.5 | 0.09 | 0.45 | 2.36 | 2.74 | 2.91 | 2.86 |
| 39 | 0.04 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.51 | 1.55 | 1.48 |
| 40 | 0.052 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.65 | 1.68 | 1.62 |
| 41 | 0.063 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.84 | 1.81 | 1.76 |
| 42 | 0.086 | 2347.5 | 0.09 | 0.185 | 2.36 | 2.15 | 2.05 | 2.03 |
| 43 | 0.109 | 2347.5 | 0.09 | 0.185 | 2.36 | 2.28 | 2.29 | 2.29 |
| 44 | 0.044 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.45 | 1.56 | 1.46 |
| 45 | 0.057 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.59 | 1.69 | 1.60 |
| 46 | 0.182 | 2347.5 | 0.09 | 0.156 | 2.36 | 2.84 | 2.86 | 2.74 |
| 47 | 0.157 | 2347.5 | 0.09 | 0.156 | 2.36 | 2.52 | 2.64 | 2.58 |
| 48 | 0.075 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.75 | 1.82 | 1.72 |
| 49 | 0.103 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.98 | 2.07 | 2.00 |
| 50 | 0.216 | 2347.5 | 0.09 | 0.131 | 2.36 | 2.89 | 3.00 | 2.72 |
| 51 | 0.023 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.45 | 1.47 | 1.59 |
| 52 | 0.060 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.14 | 2.06 | 2.17 |
| 53 | 0.070 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.40 | 2.20 | 2.32 |
| 54 | 0.109 | 2347.5 | 0.09 | 0.29 | 1.58 | 3.17 | 2.76 | 2.92 |
| 55 | 0.126 | 2347.5 | 0.09 | 0.29 | 1.58 | 3.38 | 3.00 | 3.15 |
| 56 | 0.144 | 2347.5 | 0.09 | 0.29 | 1.58 | 3.48 | 3.22 | 3.36 |
| 57 | 0.032 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.47 | 1.50 | 1.45 |
| 58 | 0.042 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.58 | 1.62 | 1.57 |
| 59 | 0.107 | 2347.5 | 0.09 | 0.29 | 3.15 | 2.49 | 2.39 | 2.38 |
| 60 | 0.109 | 2347.5 | 0.09 | 0.29 | 3.15 | 2.51 | 2.41 | 2.41 |
| 61 | 0.144 | 2347.5 | 0.09 | 0.29 | 3.15 | 2.79 | 2.78 | 2.74 |
| 62 | 0.051 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.72 | 1.69 | 1.65 |
| 63 | 0.070 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.86 | 1.90 | 1.85 |
| 64 | 0.088 | 2347.5 | 0.09 | 0.29 | 3.94 | 2.08 | 2.10 | 2.04 |
| 65 | 0.109 | 2347.5 | 0.09 | 0.29 | 3.94 | 2.3 | 2.32 | 2.23 |

**Table 4.7** Comparison between experimental and calculated (Eq. 4.5 and ANN-models) values of bed expansion ratio for bed with rod promoter

| Serial No. | System variables | | | | | | Bed expansion ratio ( $R$ ) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | $D_e / D_c$ | Exptl. | Predicted by | |
| | | | | | | | | Eq. 4.5 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 1 | 0.062 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 1.56 | 1.58 | 1.59 |
| 2 | 0.119 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 1.94 | 1.95 | 1.99 |
| 3 | 0.136 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 2.04 | 2.05 | 2.10 |
| 4 | 0.154 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 2.15 | 2.15 | 2.20 |
| 5 | 0.171 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 2.18 | 2.24 | 2.29 |
| 6 | 0.073 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 1.76 | 1.75 | 1.74 |
| 7 | 0.082 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 1.81 | 1.82 | 1.81 |
| 8 | 0.173 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 2.32 | 2.42 | 2.50 |
| 9 | 0.041 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.34 | 1.40 | 1.38 |
| 10 | 0.051 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.44 | 1.46 | 1.45 |
| 11 | 0.060 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.50 | 1.52 | 1.51 |
| 12 | 0.069 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.56 | 1.58 | 1.57 |
| 13 | 0.079 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.61 | 1.64 | 1.64 |
| 14 | 0.088 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.70 | 1.70 | 1.70 |
| 15 | 0.100 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.84 | 1.76 | 1.77 |
| 16 | 0.169 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 2.10 | 2.13 | 2.14 |
| 17 | 0.040 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.28 | 1.36 | 1.33 |
| 18 | 0.059 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.40 | 1.48 | 1.45 |
| 19 | 0.077 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.58 | 1.59 | 1.57 |
| 20 | 0.116 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.76 | 1.80 | 1.80 |
| 21 | 0.029 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.15 | 1.25 | 1.16 |
| 22 | 0.042 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.27 | 1.33 | 1.24 |
| 23 | 0.055 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.35 | 1.40 | 1.32 |
| 24 | 0.159 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.89 | 1.88 | 1.94 |
| 25 | 0.172 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.97 | 1.94 | 2.00 |
| 26 | 0.198 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 2.02 | 2.04 | 2.11 |
| 27 | 0.201 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 2.12 | 2.05 | 2.12 |
| 28 | 0.249 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 2.20 | 2.23 | 2.26 |

Continued on next page

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|
| 29 | 0.037 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.41 | 1.48 | 1.53 |
| 30 | 0.045 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.50 | 1.55 | 1.59 |
| 31 | 0.053 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.56 | 1.63 | 1.66 |
| 32 | 0.160 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 2.20 | 2.41 | 2.37 |
| 33 | 0.025 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 1.44 | 1.40 | 1.50 |
| 34 | 0.039 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 1.58 | 1.57 | 1.62 |
| 35 | 0.041 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 1.67 | 1.59 | 1.63 |
| 36 | 0.043 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.248 | 1.48 | 1.48 | 1.52 |
| 37 | 0.102 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.248 | 1.87 | 1.90 | 1.95 |
| 38 | 0.119 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.248 | 2.04 | 2.02 | 2.07 |
| 39 | 0.043 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.40 | 1.41 | 1.40 |
| 40 | 0.080 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.65 | 1.65 | 1.66 |
| 41 | 0.099 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.80 | 1.76 | 1.79 |
| 42 | 0.102 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.85 | 1.77 | 1.81 |
| 43 | 0.080 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.60 | 1.58 | 1.61 |
| 44 | 0.099 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.74 | 1.68 | 1.74 |
| 45 | 0.119 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.90 | 1.78 | 1.87 |
| 46 | 0.136 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 2.00 | 1.86 | 1.97 |
| 47 | 0.033 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.248 | 1.26 | 1.26 | 1.26 |
| 48 | 0.099 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.248 | 1.61 | 1.58 | 1.70 |
| 49 | 0.102 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.248 | 1.67 | 1.59 | 1.72 |
| 50 | 0.038 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.248 | 1.43 | 1.47 | 1.43 |
| 51 | 0.041 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.248 | 1.55 | 1.49 | 1.45 |
| 52 | 0.058 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.51 | 1.49 | 1.46 |
| 53 | 0.081 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.62 | 1.63 | 1.61 |
| 54 | 0.173 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 2.09 | 2.10 | 2.11 |
| 55 | 0.153 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 1.89 | 1.96 | 1.94 |
| 56 | 0.072 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.248 | 1.45 | 1.52 | 1.44 |
| 57 | 0.128 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.248 | 1.74 | 1.79 | 1.75 |
| 58 | 0.244 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.248 | 2.11 | 2.28 | 2.13 |
| 59 | 0.102 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 1.94 | 1.99 | 1.93 |
| 60 | 0.136 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 2.12 | 2.23 | 2.18 |
| 61 | 0.240 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 2.79 | 2.87 | 2.72 |
| 62 | 0.043 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.34 | 1.40 | 1.42 |
| 63 | 0.136 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.96 | 1.93 | 1.99 |
| 64 | 0.033 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 1.22 | 1.30 | 1.31 |
| 65 | 0.102 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 1.78 | 1.69 | 1.71 |

**Table 4.8** Comparison between experimental and calculated (Eq. 4.6 and ANN-models) values of bed expansion ratio (test data) for bed with disk promoter

| Serial No. | System variables | | | | | | | Bed expansion ratio ($R$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | $t / D_c$ | $D_k / D_c$ | Exptl. | Predicted by | |
| | | | | | | | | | Eq. 4.6 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
| 1 | 0.030 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.30 | 1.30 | 1.32 |
| 2 | 0.095 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.69 | 1.71 | 1.72 |
| 3 | 0.104 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.73 | 1.76 | 1.78 |
| 4 | 0.107 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.79 | 1.77 | 1.79 |
| 5 | 0.026 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.34 | 1.32 | 1.34 |
| 6 | 0.064 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.60 | 1.62 | 1.59 |
| 7 | 0.073 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.67 | 1.69 | 1.65 |
| 8 | 0.082 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.73 | 1.75 | 1.71 |
| 9 | 0.022 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 1.23 | 1.21 | 1.22 |
| 10 | 0.031 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 1.28 | 1.28 | 1.28 |
| 11 | 0.049 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 1.41 | 1.39 | 1.39 |
| 12 | 0.031 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 1.25 | 1.26 | 1.24 |
| 13 | 0.069 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 1.48 | 1.47 | 1.44 |
| 14 | 0.061 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 1.55 | 1.6 | 1.58 |
| 15 | 0.071 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 1.63 | 1.67 | 1.64 |
| 16 | 0.080 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 1.68 | 1.73 | 1.70 |
| 17 | 0.090 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 1.72 | 1.79 | 1.76 |
| 18 | 0.05 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.38 | 1.40 | 1.40 |
| 19 | 0.068 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.52 | 1.50 | 1.51 |
| 20 | 0.078 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.57 | 1.56 | 1.56 |
| 21 | 0.087 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.59 | 1.61 | 1.62 |
| 22 | 0.096 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.64 | 1.65 | 1.67 |
| 23 | 0.069 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.770 | 1.48 | 1.47 | 1.47 |
| 24 | 0.059 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.28 | 1.37 | 1.31 |
| 25 | 0.162 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.84 | 1.8 | 1.83 |
| 26 | 0.201 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.94 | 1.94 | 1.97 |
| 27 | 0.228 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 2.05 | 2.03 | 2.04 |
| 28 | 0.086 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.77 | 1.79 | 1.82 |

Continued on next page

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 29 | 0.117 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.97 | 2.00 | 2.01 |
| 30 | 0.133 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 2.11 | 2.09 | 2.10 |
| 31 | 0.148 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 2.17 | 2.19 | 2.18 |
| 32 | 0.165 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 2.25 | 2.28 | 2.26 |
| 33 | 0.032 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.55 | 1.42 | 1.53 |
| 34 | 0.075 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.82 | 1.81 | 1.83 |
| 35 | 0.088 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.95 | 1.91 | 1.92 |
| 36 | 0.102 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 2.11 | 2.02 | 2.01 |
| 37 | 0.048 | 2347.5 | 0.129 | 0.29 | 2.36 | 0.125 | 0.551 | 1.52 | 1.46 | 1.55 |
| 38 | 0.104 | 2347.5 | 0.129 | 0.29 | 2.36 | 0.125 | 0.551 | 1.88 | 1.81 | 1.9 |
| 39 | 0.141 | 2347.5 | 0.129 | 0.29 | 2.36 | 0.125 | 0.551 | 2.08 | 2.02 | 2.10 |
| 40 | 0.030 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 1.26 | 1.27 | 1.23 |
| 41 | 0.095 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 1.61 | 1.65 | 1.62 |
| 42 | 0.141 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 1.89 | 1.88 | 1.87 |
| 43 | 0.067 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 1.37 | 1.45 | 1.38 |
| 44 | 0.095 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 1.58 | 1.58 | 1.54 |
| 45 | 0.124 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 1.78 | 1.71 | 1.70 |
| 46 | 0.048 | 2347.5 | 0.014 | 0.29 | 2.36 | 0.125 | 0.551 | 1.20 | 1.30 | 1.22 |
| 47 | 0.104 | 2347.5 | 0.014 | 0.29 | 2.36 | 0.125 | 0.551 | 1.47 | 1.53 | 1.54 |
| 48 | 0.096 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 1.65 | 1.64 | 1.65 |
| 49 | 0.130 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 1.80 | 1.80 | 1.81 |
| 50 | 0.142 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 1.88 | 1.85 | 1.86 |
| 51 | 0.131 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 1.77 | 1.77 | 1.78 |
| 52 | 0.194 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 2.05 | 2.03 | 1.99 |
| 53 | 0.102 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.60 | 1.61 | 1.63 |
| 54 | 0.186 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.93 | 1.96 | 1.93 |
| 55 | 0.200 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.95 | 2.01 | 1.96 |
| 56 | 0.243 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 2.03 | 2.17 | 2.04 |
| 57 | 0.020 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.32 | 1.27 | 1.31 |
| 58 | 0.067 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.62 | 1.66 | 1.62 |
| 59 | 0.124 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.98 | 2.05 | 1.97 |
| 60 | 0.048 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 1.40 | 1.37 | 1.38 |
| 61 | 0.067 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 1.50 | 1.48 | 1.49 |
| 62 | 0.03 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 1.19 | 1.23 | 1.21 |
| 63 | 0.067 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 1.43 | 1.43 | 1.42 |
| 64 | 0.104 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 1.56 | 1.60 | 1.62 |
| 65 | 0.107 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 1.59 | 1.61 | 1.63 |

**Table 4.9** Comparison between experimental and calculated (Eq. 4.7 and ANN-model) values of bed expansion ratio for bed with blade promoter

| Serial No. | System variables | | | | | Bed expansion ratio ( $R$ ) | | |
|---|---|---|---|---|---|---|---|---|
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | Exptl. | Predicted by | |
| | | | | | | | Eq. 4.7 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 0.081 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.54 | 1.55 | 1.59 |
| 2 | 0.100 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.63 | 1.64 | 1.69 |
| 3 | 0.102 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.65 | 1.65 | 1.71 |
| 4 | 0.070 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.31 | 1.38 | 1.38 |
| 5 | 0.096 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.47 | 1.48 | 1.52 |
| 6 | 0.122 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.55 | 1.57 | 1.65 |
| 7 | 0.148 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.72 | 1.66 | 1.77 |
| 8 | 0.161 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.79 | 1.70 | 1.82 |
| 9 | 0.227 | 1409.2 | 0.09 | 0.29 | 2.36 | 2.11 | 1.90 | 2.04 |
| 10 | 0.046 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.41 | 1.43 | 1.48 |
| 11 | 0.063 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.53 | 1.54 | 1.59 |
| 12 | 0.082 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.61 | 1.65 | 1.71 |
| 13 | 0.113 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.91 | 1.83 | 1.90 |
| 14 | 0.128 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.05 | 1.91 | 1.99 |
| 15 | 0.144 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.20 | 1.99 | 2.08 |
| 16 | 0.043 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.49 | 1.46 | 1.53 |
| 17 | 0.051 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.52 | 1.52 | 1.59 |
| 18 | 0.062 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.58 | 1.6 | 1.66 |
| 19 | 0.044 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.37 | 1.37 | 1.45 |
| 20 | 0.081 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.67 | 1.59 | 1.68 |
| 21 | 0.091 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.74 | 1.64 | 1.74 |
| 22 | 0.172 | 2347.5 | 0.129 | 0.29 | 2.36 | 2.15 | 2.02 | 2.17 |
| 23 | 0.062 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.41 | 1.42 | 1.40 |
| 24 | 0.072 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.47 | 1.47 | 1.45 |
| 25 | 0.081 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.51 | 1.51 | 1.51 |
| 26 | 0.120 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.69 | 1.68 | 1.72 |
| 27 | 0.154 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.82 | 1.82 | 1.89 |
| 28 | 0.044 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.25 | 1.29 | 1.24 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 29 | 0.072 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.41 | 1.42 | 1.39 |
| 30 | 0.081 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.45 | 1.46 | 1.45 |
| 31 | 0.091 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.49 | 1.50 | 1.50 |
| 32 | 0.137 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.69 | 1.68 | 1.74 |
| 33 | 0.062 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.28 | 1.33 | 1.30 |
| 34 | 0.072 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.38 | 1.37 | 1.35 |
| 35 | 0.100 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.44 | 1.47 | 1.50 |
| 36 | 0.102 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.50 | 1.48 | 1.52 |
| 37 | 0.137 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.63 | 1.59 | 1.69 |
| 38 | 0.118 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.68 | 1.66 | 1.66 |
| 39 | 0.130 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.75 | 1.705 | 1.71 |
| 40 | 0.153 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.82 | 1.794 | 1.8 |
| 41 | 0.179 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.85 | 1.89 | 1.89 |
| 42 | 0.129 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.61 | 1.68 | 1.66 |
| 43 | 0.154 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.78 | 1.77 | 1.76 |
| 44 | 0.179 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.82 | 1.86 | 1.84 |
| 45 | 0.208 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.92 | 1.96 | 1.91 |
| 46 | 0.254 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.98 | 2.11 | 1.99 |
| 47 | 0.059 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.28 | 1.37 | 1.31 |
| 48 | 0.073 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.35 | 1.43 | 1.38 |
| 49 | 0.101 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.45 | 1.54 | 1.51 |
| 50 | 0.271 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.98 | 2.12 | 1.94 |
| 51 | 0.081 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.74 | 1.73 | 1.64 |
| 52 | 0.102 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.91 | 1.87 | 1.77 |
| 53 | 0.120 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.93 | 1.98 | 1.88 |
| 54 | 0.154 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.01 | 2.17 | 2.07 |
| 55 | 0.172 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.08 | 2.27 | 2.16 |
| 56 | 0.053 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.34 | 1.33 | 1.37 |
| 57 | 0.072 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.45 | 1.41 | 1.47 |
| 58 | 0.081 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.51 | 1.45 | 1.52 |
| 59 | 0.137 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.79 | 1.66 | 1.80 |
| 60 | 0.154 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.82 | 1.72 | 1.87 |
| 61 | 0.172 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.88 | 1.78 | 1.93 |
| 62 | 0.072 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.38 | 1.35 | 1.40 |
| 63 | 0.091 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.49 | 1.42 | 1.49 |
| 64 | 0.120 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.62 | 1.51 | 1.62 |
| 65 | 0.154 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.74 | 1.61 | 1.75 |

**Table 4.10** Mean and standard deviations

| Bed particulars | Standard deviation | | Mean | | No. of data |
|---|---|---|---|---|---|
| | Dimensional Analysis method | ANN-Model | Dimensional Analysis method | ANN-Model | |
| UP | 4.53 | 3.18 | 3.62 | 2.47 | 147 |
| RP | 3.75 | 3.004 | 3.02 | 2.278 | 203 |
| DP | 2.48 | 1.828 | 1.87 | 1.405 | 248 |
| BP | 4.48 | 0.230 | 3.63 | 2.269 | 156 |

**Table 4.11** Comparison between calculated (Eqs. 4.2-4.5) values of bed expansion ratio for unpromoted bed and beds with rod, disk and blade type promoters

| Sl. No | Variables | Constants: $\rho_s/\rho_f$ =2347.5, $A_{do}/A_c$=0.09,$d_p/d_o$=0.29, $h_s/D_c$=2.36,$D_e/D_c$=1.248,$t/D_c$=0.125,$D_k/D_c$=0.551 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $G_R$ | Predicted values of bed Expansion ratio, R | | | | % reduction in R over corresponding unpromoted bed | | |
| | | UP | RP | DP | BP | RP | DP | BP |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 0.02 | 1.37 | 1.25 | 1.22 | 1.20 | 8.26 | 10.67 | 12.27 |
| 2 | 0.05 | 1.80 | 1.50 | 1.44 | 1.39 | 16.62 | 20.01 | 22.82 |
| 3 | 0.08 | 2.19 | 1.71 | 1.62 | 1.55 | 22.06 | 25.86 | 29.38 |
| 4 | 0.10 | 2.44 | 1.83 | 1.74 | 1.64 | 24.79 | 28.76 | 32.62 |
| 5 | 0.12 | 2.68 | 1.96 | 1.85 | 1.74 | 27.07 | 31.14 | 35.26 |
| 6 | 0.15 | 3.03 | 2.13 | 2.00 | 1.87 | 29.86 | 34.03 | 38.47 |
| 7 | 0.20 | 3.59 | 2.39 | 2.24 | 2.07 | 33.40 | 37.66 | 42.48 |
| 8 | 0.25 | 4.14 | 2.64 | 2.47 | 2.26 | 36.08 | 40.36 | 45.45 |
| | $\rho_s/\rho_f$ | Constants: $G_R$=0.1, $A_{do}/A_c$=0.09, $d_p/d_o$=0.29, $h_s/D_c$=2.36,$D_e/D_c$=1.248, $t/D_c$=0.125, $D_k/D_c$=0.551 | | | | | | |
| 9 | 1409.17 | 2.07 | 1.63 | 1.55 | 1.50 | 21.21 | 24.73 | 27.55 |
| 10 | 3245.83 | 2.74 | 2.00 | 1.88 | 1.76 | 27.06 | 31.29 | 35.85 |
| 11 | 4066.67 | 2.99 | 2.14 | 2.00 | 1.85 | 28.60 | 33.00 | 38.07 |

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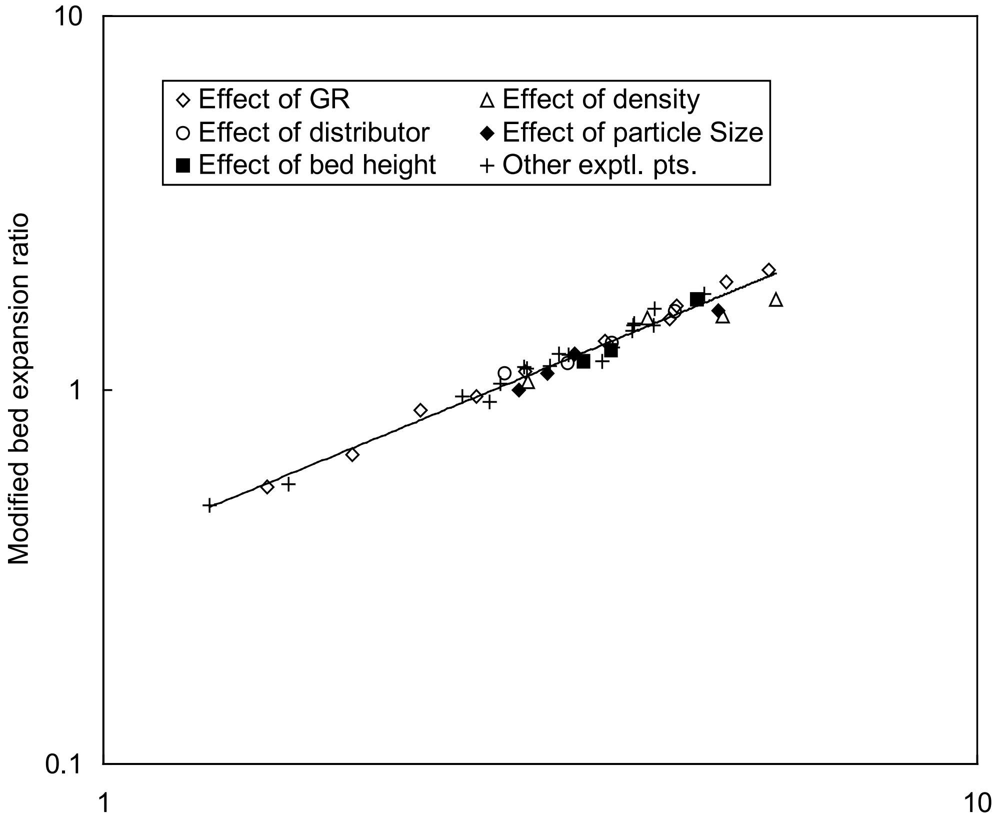
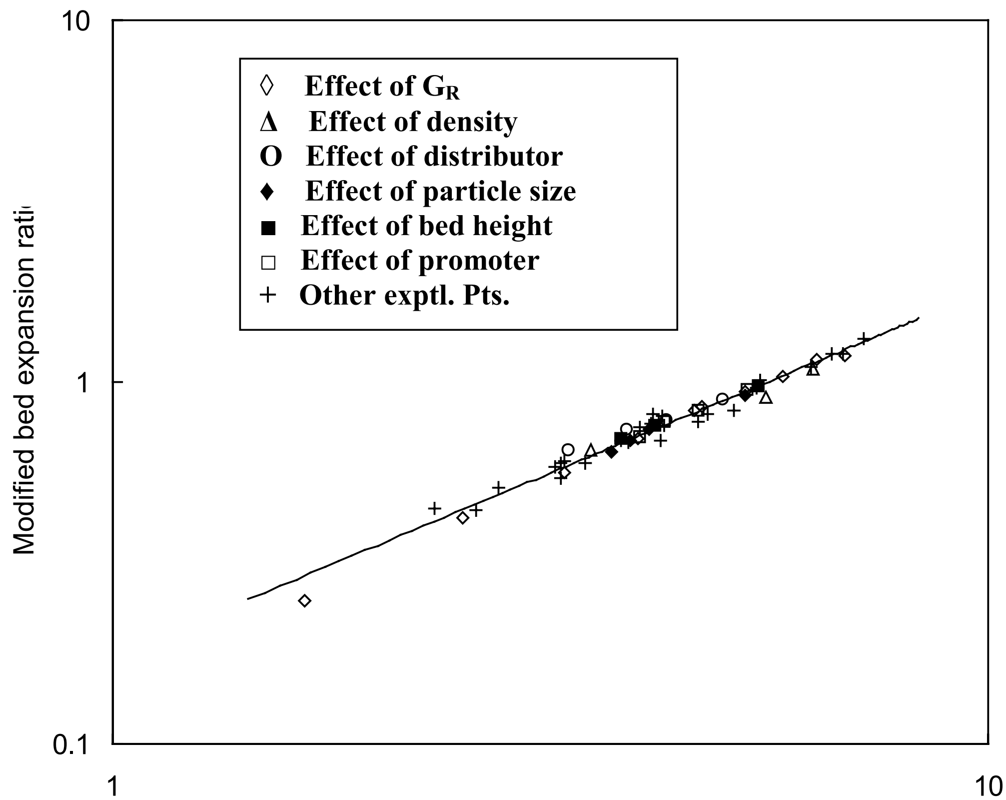
| (1) | (2) | | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| | $A_{do}/A_c$ | | Constants: $G_R$=0.1, $\rho_s/\rho_f$ =2347.5, $d_p/d_o$=0.29, $h_s/D_c$=2.36 $D_e/D_c$=1.248, $t/D_c$=0.125, $D_k/D_c$=0.551 | | | | | | |
| 12 | 0.129 | | 2.546 | 1.89 | 1.79 | 1.69 | 25.65 | 29.72 | 33.86 |
| 13 | 0.057 | | 2.313 | 1.77 | 1.68 | 1.60 | 23.71 | 27.54 | 31.03 |
| 14 | 0.032 | | 2.170 | 1.69 | 1.61 | 1.54 | 22.33 | 26.00 | 29.05 |
| 15 | 0.014 | | 1.992 | 1.59 | 1.52 | 1.47 | 20.38 | 23.79 | 26.25 |
| | $d_p/d_o$ | | Constants: $G_R$=0.1, $\rho_s/\rho_f$ =2347.5, $A_{do}/A_c$=0.09, $h_s/D_c$=2.36, $D_e/D_c$=1.248, $t/D_c$=0.125, $D_k/D_c$=0.551 | | | | | | |
| 16 | 0.45 | | 2.72 | 1.95 | 1.83 | 1.71 | 28.48 | 32.91 | 37.25 |
| 17 | 0.185 | | 2.20 | 1.73 | 1.66 | 1.58 | 21.14 | 24.61 | 27.94 |
| 18 | 0.156 | | 2.12 | 1.70 | 1.63 | 1.56 | 19.80 | 23.08 | 26.21 |
| 19 | 0.131 | | 2.04 | 1.66 | 1.56 | 1.54 | 18.46 | 21.53 | 24.45 |
| | $h_s/D_c$ | | Constants: $G_R$=0.1, $\rho_s/\rho_f$ =2347.5, $A_{do}/A_c$=0.09, $d_p/d_o$=0.29, $D_e/D_c$=1.248, $t/D_c$=0.125, $D_k/D_c$=0.551 | | | | | | |
| 20 | 1.58 | | 2.64 | 1.98 | 1.89 | 1.86 | 24.91 | 28.28 | 29.61 |
| 21 | 3.15 | | 2.31 | 1.74 | 1.64 | 1.52 | 24.60 | 28.90 | 34.07 |
| 22 | 3.94 | | 2.22 | 1.68 | 1.58 | 1.45 | 24.39 | 28.89 | 34.85 |
| | $D_e/D_c$ | $t/D_c$ | Constants: $G_R$=0.1, $\rho_s/\rho_f$ =2347.5, $A_{do}/A_c$=0.09, $d_p/d_o$=0.29, $h_s/D_c$=2.36, $D_k/D_c$=0.551 | | | | | | |
| 23 | 2.209 | 0.063 | 2.44 | 1.95 | 1.87 | — | 19.99 | 23.29 | — |
| 24 | 0.856 | 0.188 | 2.44 | 1.77 | 1.67 | — | 27.64 | 31.56 | — |
| 25 | 0.642 | 0.250 | 2.44 | 1.72 | 1.62 | — | 29.64 | 33.39 | — |
| | $D_e/D_c$ | $D_k/D_c$ | Constants: $G_R$=0.1, $\rho_s/\rho_f$ =2347.5, $A_{do}/A_c$=0.09, $d_p/d_o$=0.29, $h_s/D_c$=2.36, $t/D_c$=0.125 | | | | | | |
| 26 | 2.209 | 0.398 | 2.44 | 1.95 | 1.86 | — | 19.99 | 23.63 | — |
| 27 | 0.856 | 0.669 | 2.44 | 1.77 | 1.67 | — | 27.64 | 31.45 | — |
| 28 | 0.642 | 0.770 | 2.44 | 1.71 | 1.63 | — | 29.64 | 33.25 | — |




$$\left(G_R\right)^{0.888}\left(\frac{\rho_s}{\rho_f}\right)^{0.615}\left(\frac{A_{do}}{A_c}\right)^{0.202}\left(\frac{d_p}{d_o}\right)^{0.425}\left(\frac{h_s}{D_c}\right)^{-0.329}$$

**Fig. 4.1** Variation of modified bed expansion ratio $\left(R'\right)$ with system parameters for unpromoted bed




$$(G_R)^{0.726}\left(\frac{\rho_s}{\rho_f}\right)^{0.553}\left(\frac{A_{do}}{A_c}\right)^{0.183}\left(\frac{d_p}{d_o}\right)^{0.284}\left(\frac{h_s}{D_c}\right)^{-0.396}\left(\frac{D_e}{D_c}\right)^{0.229}$$

**Fig. 4.2** Variation of modified bed expansion ratio $\left(R'\right)$ with system parameters for bed with rod promoter

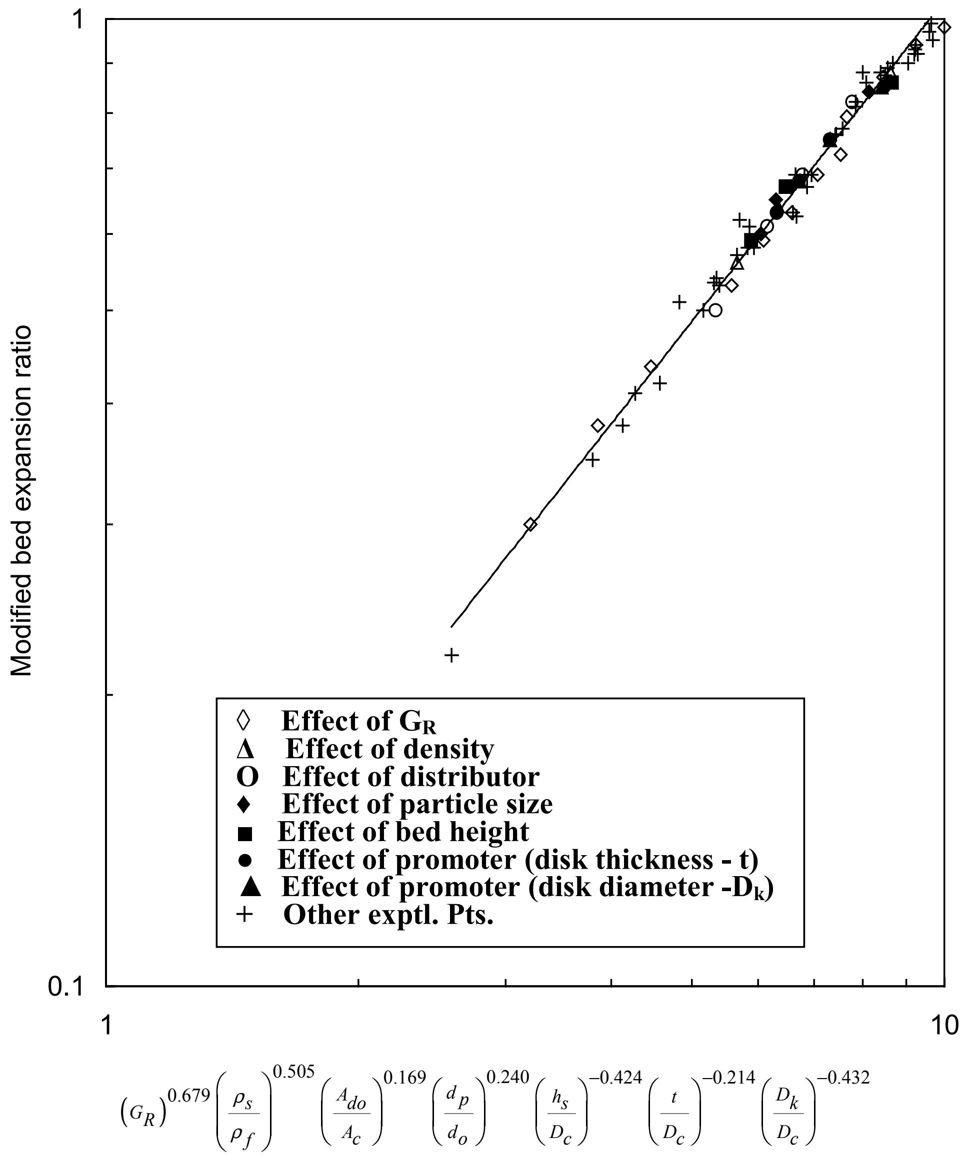



**Fig. 4.3** Variation of modified bed expansion ratio $\left(R'\right)$ with system parameters for bed with disk promoter

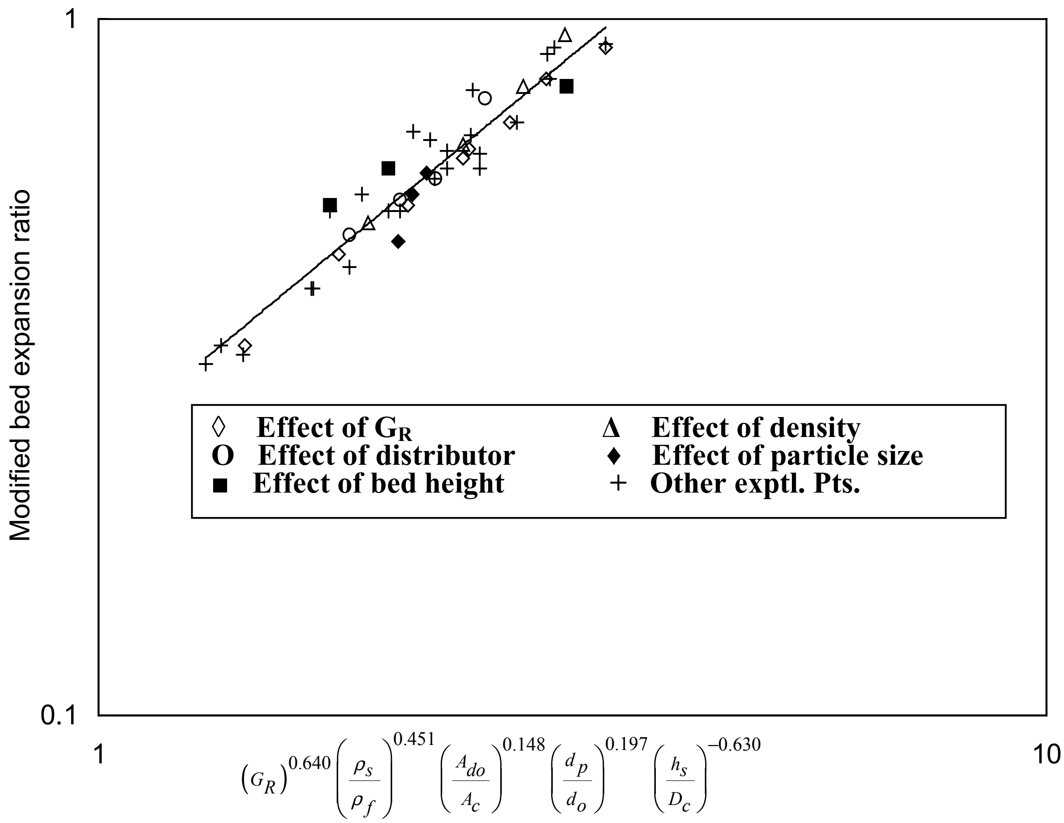



**Fig. 4.4** Variation of modified bed expansion ratio $\left(R'\right)$ with system parameters for bed with blade promoter

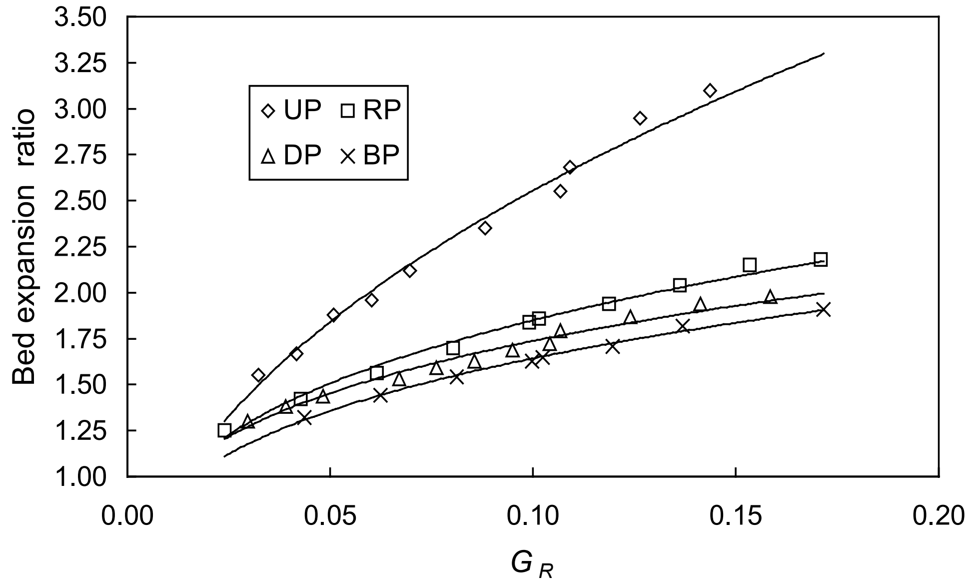



Fig. 4.5 Variation of bed expansion ratio ( R ) with flow parameter ($G_R$) for different beds

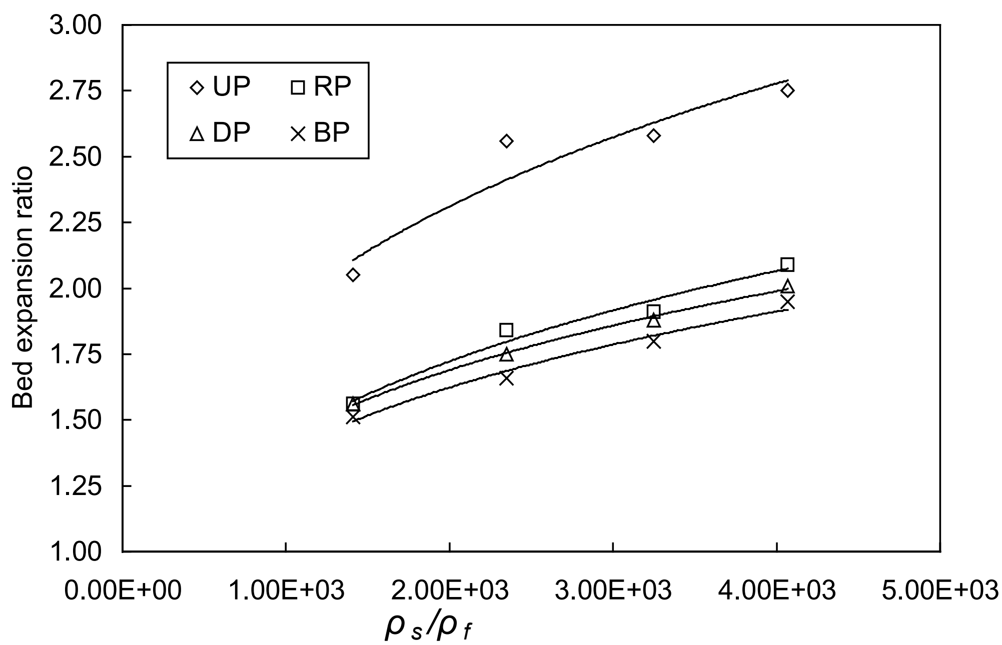



**Fig. 4.6** Variation of bed expansion ratio ( R ) with density parameter ($\rho_s/\rho_f$) for different beds

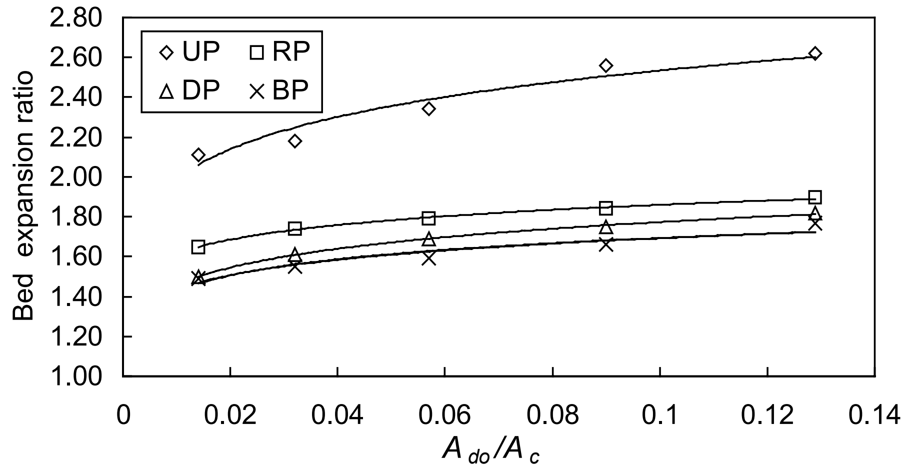



**Fig. 4.7** Variation of bed expansion ratio ( $R$ ) with distributor parameter ($A_{do}/A_c$) for different beds

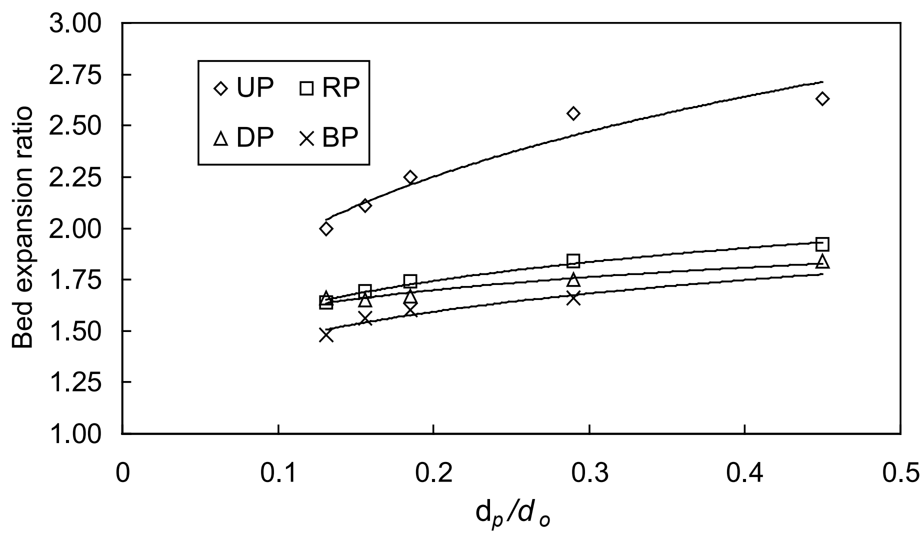



**Fig. 4.8** Variation of bed expansion ratio ( $R$ ) with size parameter ($d_p/d_o$) for different beds

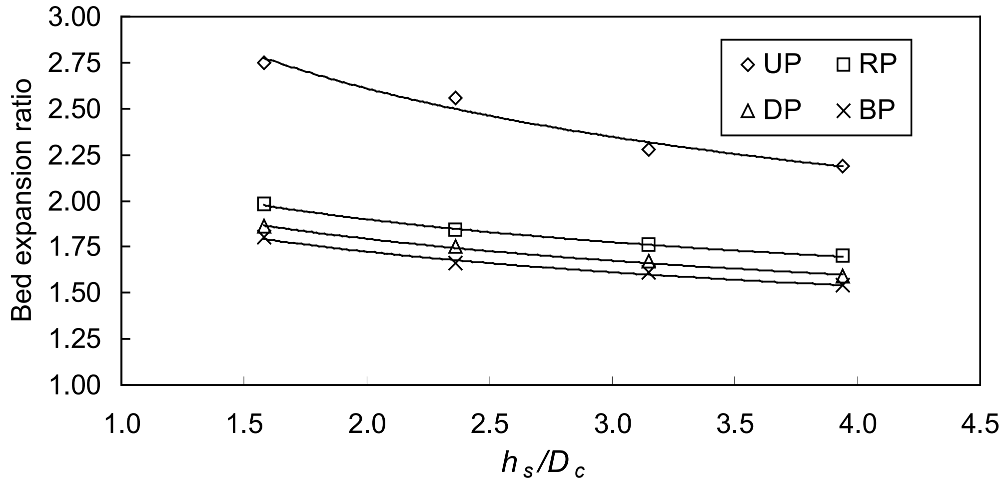



**Fig. 4.9** Variation of bed expansion ratio ( $R$ ) with bed height parameter ($h_s/D_c$) for different beds

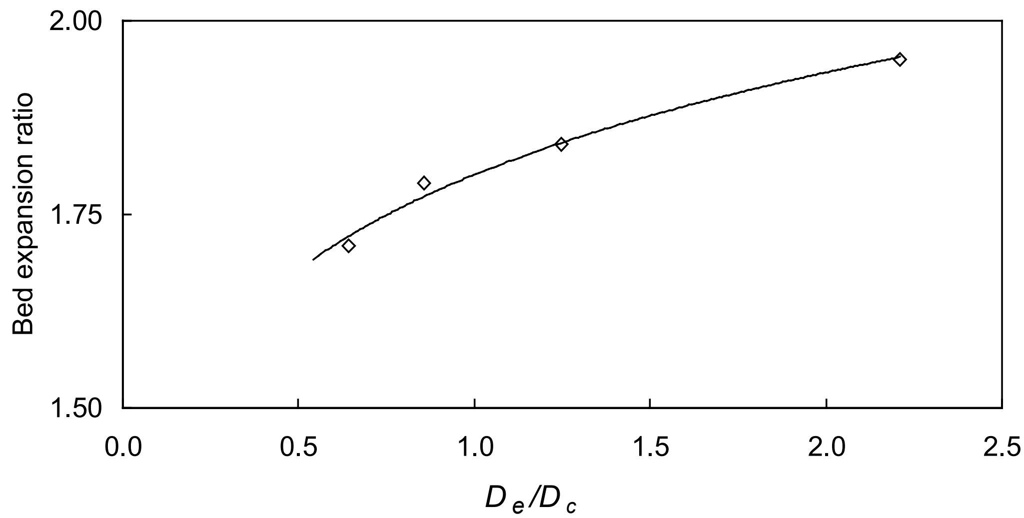



**Fig. 4.10** Variation of bed expansion ratio ( $R$ ) with rod promoter parameter ($D_e/D_c$)

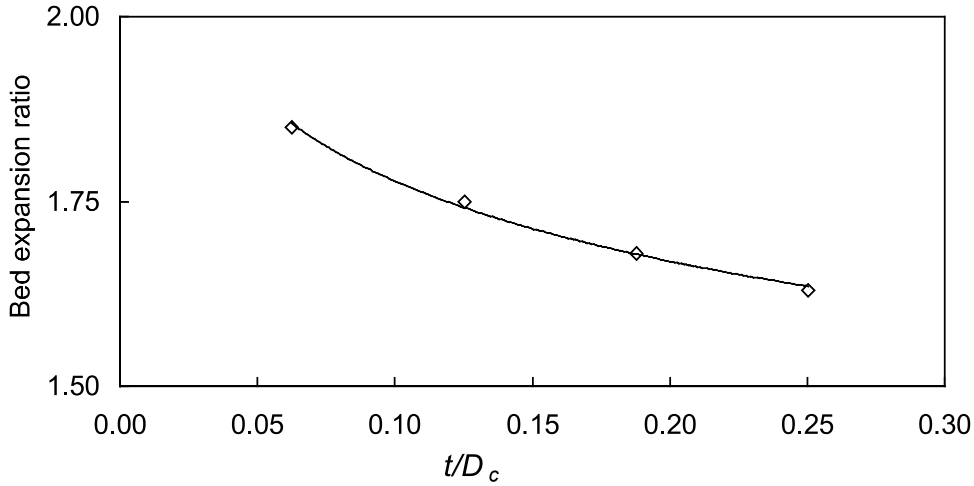



**Fig. 4.11** Variation of bed expansion ratio ( $R$ ) with disk thick-
ness parameter ($D_k/D_c$) for bed with disk

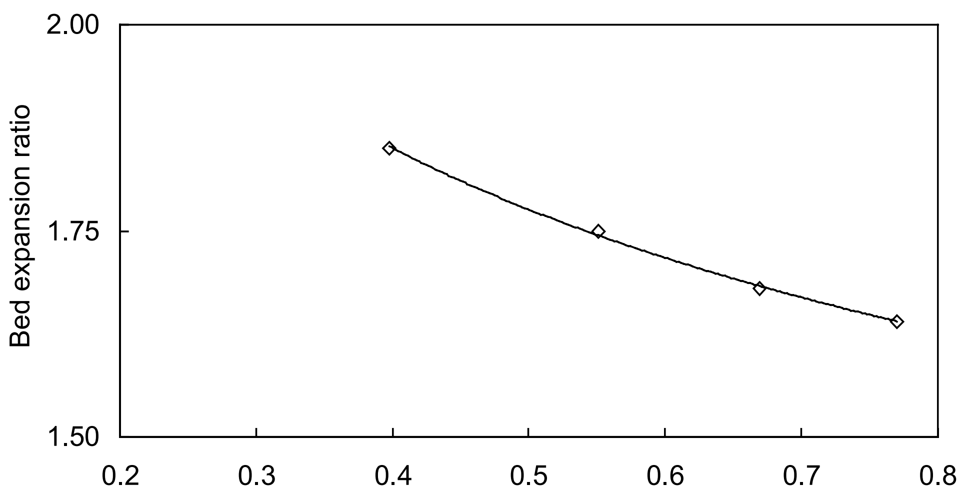



**Fig. 4.12** Variation of bed expansion ratio ( R ) with diameter parameter ($D_k/D_c$) for beds with disk promoter

# CHAPTER V
# Prediction of fluctuation ratio

## 5.1 General

Gas flow in a gas-solid fluidized bed is characterized by the predominance of bubbles. This flow with bubbles exhibits considerable bed fluctuation at fluid mass velocity higher than the minimum fluidization mass velocity leading to unstability in operation, which affects the fluidization quality adversely.

### 5.1.1 Fluctuation ratio and fluidization quality

Two methods are available to quantify fluidization quality viz. the uniformity index method and the fluctuation ratio method. In case of uniformity index method, the quality of fluidization depends on the index value. Uniformity index of unity indicates high degree of uniformity where as uniformity index between 1-5 and 5-60 corresponds to fair and poor degree of uniformity respectively. For perfect uniformity, the index has a value of zero. The quality of fluidization and hence the fluidization performance deteriorates with increase in the value of uniformity index. Martin and Andrieu [1] concluded that:

(i) The uniformity index is directly proportional to height above the gas inlet.
(ii) The local uniformity index at any specific position in the bed is little or not at all influenced by bed height.
(iii)The uniformity index is proportional to the logarithm of the supercial gas velocity.

Fluctuation ratio method has been used widely because of more exact quantification of fluidization quality. Fluctuation ratio is defined as the ratio of the highest and the lowest levels which the top of a fluidized bed occupies for any particular gas flow rate above the minimum fluidization velocity.

Leva [1] made an attempt to correlate fluctuation ratio to bed characteristics, as under:

$$r = e^{m \frac{G_f - G_{mf}}{G_{mf}}} \tag{5.1}$$

the slope 'm' was related to particle diameter.

Beyond certain limiting value of $\frac{G_f - G_{mf}}{G_{mf}}$, the top oscillation is also influenced by slugging. The fluctuation ratio pertaining to the slugging zone follow smoothly from the non-slugging zone. Since slugging is to be affected by the 'aspect ratio', the fluctuation ratio is dependent on this also [1].

Bed fluctuation and fluidization quality being inter-related, previous investigations on quality have been aimed at development of correlations for fluctuation ratio in terms of static and dynamic parameters of the system for cylindrical [2], baffled (promoted)-cylindrical [2. 3], conical [2, 4, 5] and non-cylindrical beds [6]. Dimensionless groups like $\frac{d_p}{D_c}$, ($d_{pm}$ in case of mixtures), $\frac{h_s}{D_c}$ (aspect ratio), $\frac{\rho_s}{\rho_f}$ ($\rho_{sm}$ in case of mixtures), velocity ratio $\frac{G_f}{G_{mf}}$ or excess velocity ratio $\frac{G_f - G_{mf}}{G_{mf}}$ and the tangent of the cone angle in case of conical bed have been used in the a-fore-said correlations.

The following two broad conclusions have been made in the above investigations:

(i) A substantial decrease in fluctuation ratio (and hence an increase in the fluidization quality) was observed in baffled (promoted)-cylindrical and conical beds as compared to a columnar unbaffled (unpromoted) bed.

(ii) Less bed fluctuation was marked in case of homogeneous and heterogeneous binaries in comparison to their monosize counterparts under identical fluidizing conditions.

Although some qualitative explanation and quantitative expressions relating to fluidization quality have been presented in terms of some of the bed parameters for unpromoted cylindrical, conical and non-cylindrical beds and a f ew for promoted conventional columnar beds by the previous investigators, the detailed effects of various operational (both static and dynamic) parameters in case of promoted beds remain almost unexplored. With this end in view, studies relating to quantification of fluidization quality in term of fluctuation ratio for the case of four rod promoters, seven disk promoters with different spacing and configuration and one blade promoter supported by five different distributors of varying aperture size have been taken up.

### 5.1.2 Factors affecting fluidization quality

**A. Effect of Gas Velocity**

Gas velocity has considerable effect on bubble size and slugging characteristic of a gas-solid fluidized bed. Bubble velocity as found out by various investigators has been listed by Kuni and Levenspiel [7]. The rising velocity of an isolated bubble is given by Rowe and Partridge [8] as-

$$U_b = 0.57 \textit{ to } 0.85\left(gd_p\right)^{0.5} \tag{5.2}$$

**B. Effect of bed height**

In deep beds of dense material, the pressure drop is high as compared to the weight of the bed per unit area. The pressure difference is large with respect to the average static operating pressure.

**C. Effect of pressure and temperature**

The static operating pressure has an influence on bed behaviour. As density of fluidizing gas is increased, and the solid-fluid density difference correspondingly reduced by increasing the static operating pressure, a condition is reached when bubbling is entirely suppressed. As a result, the drop across a deep bed is small as compared to the absolute static pressure.

The quality of fluidization is improved at high temperatures [9]. But use of high pressure and elevated temperature to obtain better quality is not practicable bacause of other process constraints.

**D. Effect of particle properties**

The quality of fluidization is improved with low density and fine size particles. There is nothing ideal about the fluidization property of closely sized, dense spherical particles, which tend to fluidize in a very unstable manner. It is generally accepted that some breadth of the range of particle diameter is desirable in order to obtain more stable fluidization. The broad size distribution corresponds to the regime of materials which fluidize to give good bed fluidity. For small particles, the quality deteriorates in the form of flocculation of particles into porous transient lumps and for larger particles, the deterioration of quality is due to aggregation of particles. Unlike laboratory ones, industrial fluidized beds contain a wide range of particle sizes and attrition of particle size exists.

**E. Effect of fluid properties**

Gas fluidized beds unlike liquid fluidized beds tend to bubble due to high ratio of particle to fluid density. The degree of solid mixing tends to increase with increase in viscosity. So gases of high viscosity and density promote the quality of fluidization.

**F. Effect of distributor design**

An important function of the gas distributor is to promote uniform fluidization by applying a stabilizing effect on the distribution of fluidizing gas. Poor distributor design may develop highly non-uniform fluidization due to channelling, bubbling or slugging. The primary function of the distributor is to introduce the fluidizing gas to the fluidizer in a uniform manner. It also provides support to the material in the bed. A well-designed distributor prevents the back-flow of the particles and gives low but sufficient pressure drop for stable fluidization. Masters [10] explained the importance of properly designed gas distributor plate in the use of a fluidized bed. On the basis of advantages and disadvantages, he studied the performance of different air distributor plates viz. perforated plate, gill plates (punched hole plates), flex plates (variation of the gill plate), and non-sifting flex plate (variation of the flex plate) considering various aspects. He expressed that, in spite of much development in plate design, the perforated plate is still in use as standard fluidized bed distributor plate due to limited available literature on the other types of distributor plates. From the experimental results on particle mixing and segregation in a gas-solid fluidized bed, Wang and Huang [11] observed that the perforated plate with low open area or less number of holes perform better. Different investigators have proposed a wide range of distributor-to-bed pressure drop ratio for bed stability and to provide more uniform fluidization (detailed explanation in chapter-VI)

In the present work, an attempt has made to develop correlations for fluctuation ratio in case of unpromoted bed and beds promoted with blade (one number), rod (four numbers) and disk (seven numbers) promoters supported on five different distributors of varying open area (Table 3.1).

## 5.2 Development of correlations

For the development of correlations for bed fluctuation ratio ($r$), the modified bed fluctuation ratio ($r'$), has been used in order to ensure zero fluctuation at the onset of fluidization i.e. at zero excessive mass velocity. From dimensional analysis, ($r'$), can be ralated to the system parameters as follows:

$$r' = \phi\left( G_R, \frac{\rho_s}{\rho_f}, \frac{A_{do}}{A_c}, \frac{d_p}{d_o}, \frac{h_s}{D_c}, \frac{D_e}{D_c}, \frac{t}{D_c}, \frac{D_k}{D_c} \right) \tag{5.3}$$

or,

$$r' = \mathrm{K}\left(G_R\right)^a \left(\frac{\rho_s}{\rho_f}\right)^b \left(\frac{A_{do}}{A_c}\right)^c \left(\frac{d_p}{d_o}\right)^d \left(\frac{h_s}{D_c}\right)^e \left(\frac{D_e}{D_c}\right)^f \left(\frac{t}{D_c}\right)^g \left(\frac{D_k}{D_c}\right)^h \tag{5.4}$$

Analyzing the experimental data for the effect of the individual dimensionless parameters, the values of the constants and the exponents (chapter 3: data processing) have been obtained by the regression analysis of the data for the respective beds. Using correlation plots (Figs. 5.1 to 5.4), the final expressions for modified bed fluctuation ratio for the unpromoted and the promoted beds with rod, disk and blade promoters have been obtained as under:

**Unpromoted bed**

$$r' = 0.24\left(G_R\right)^{0.85} \left(\frac{\rho_s}{\rho_f}\right)^{0.63} \left(\frac{A_{do}}{A_c}\right)^{0.21} \left(\frac{d_p}{d_o}\right)^{0.41} \left(\frac{h_s}{D_c}\right)^{-0.36} \tag{5.5}$$

**Bed with rod promoter**

$$r' = 0.16\left(G_R\right)^{0.69} \left(\frac{\rho_s}{\rho_f}\right)^{0.50} \left(\frac{A_{do}}{A_c}\right)^{0.13} \left(\frac{d_p}{d_o}\right)^{0.25} \left(\frac{h_s}{D_c}\right)^{-0.38} \left(\frac{D_e}{D_c}\right)^{0.27} \tag{5.6}$$

**Bed with disk promoter:**

$$r' = 0.09\left(G_R\right)^{0.67} \left(\frac{\rho_s}{\rho_f}\right)^{0.46} \left(\frac{A_{do}}{A_c}\right)^{0.14} \left(\frac{d_p}{d_o}\right)^{0.24}$$

$$\mathrm{X}\left(\frac{h_s}{D_c}\right)^{-0.46} \left(\frac{t}{D_c}\right)^{-0.23} \left(\frac{D_k}{D_c}\right)^{-0.67} \tag{5.7}$$

**Bed with blade promoter:**

$$r' = 0.29\left(G_R\right)^{0.51} \left(\frac{\rho_s}{\rho_f}\right)^{0.33} \left(\frac{A_{do}}{A_c}\right)^{0.13} \left(\frac{d_p}{d_o}\right)^{0.18} \left(\frac{h_s}{D_c}\right)^{-0.67} \tag{5.8}$$

### 5.2.1 Development and use of artificial neural network models

The experimental data of bed fluctuation ratio has been used to develop artificial neural network (ANN) models, on similar lines as explained in article 4.2.1. In this chapter, four such ANN-models: one each for unpromoted bed and beds promoted with rod, disk and blade promoters, for the prediction of bed fluctuation have been

developed. Tables 5.1-5.4 present the sum-squared error (SSE) for different ANN structures (I X H XO) and Table 5.5 the selected ANN structures based on least error criterion for different beds. The comparison between the predicted values of bed fluctuation using ANN-models and the corresponding experimental ones (Tables 5.6 - 5.9) show the satisfactory training level of models. Also, the values of the co-efficient of determination ( $R^2$ ) for training and testing data in case of unpromoted bed and beds promoted with rod, disk and blade promoters which were obtained respectively as (0.9592, 0.9289), (0.9651, 0.9406), (0.9518, 0.9525 ) and (0.8742, 0.8739 ), support the above claim.

## 5.3 Results and Discussion

The comparative variation of bed fluctuation ratio ( $r$ ) with non- dimensional system parameters for different beds have been shown in Figs. 5.5 to 5.9 and with rod and disk promoter parameters in Figs. 5.10 to 5.12 under identical operating conditions. The values of bed fluctuation ratio calculated with the help of developed correlations for unpromoted bed and beds with rod, disk and blade type of promoters have been compared with the corresponding experimental ones and those predicted from ANN-models (Tables 5.6 to 5.9 for randomized data). From the comparison Tables 5.6-5.9, the predicted results using developed correlations have been found to be in good agreement with the corresponding experimental ones and those predicted by ANN-models. The mean and standard deviation of the experimental values from the calculated ones (using the above two methods) for bed fluctuation ratio in case of unpromoted and promoted beds with rod, disk and blade promoters have been given in Table 5.10.

Further, it is observed that the developed correlations using dimensional analysis approach as well as ANN-models can be satisfactorily used for the prediction for bed fluctuation ratio in the respective beds. From the Table 5.10, it has been found that the prediction by ANN-models provide better values with reduced standard and mean deviations in most of the cases. But an ANN-model is only a system which can not be represented by a physical correlation. On the other hand, dimensional analysis method provide satisfactory prediction as well as correlations which show inter-relation between the dependent and independent variables of the system, and hence can be used more conveniently.

It is evident from the developed correlations and Figs. 5.5-5.12 that the bed fluctuation is significantly influenced by the distributor and promoter parameters in addition to other system parameters. As observed, the reduction in bed fluctuation in case of the promoted beds over the unpromoted one can be attributed to the breaking up of bubbles and controlling their size and growth. The radial promoter elements facilitate smooth fluidization with negligible channelling and slugging compared to an unpromoted bed and the beds with rod type promoter. The reduction of bed fluctuation with the increase in blockage volume by the promoters in terms of larger number of rods in the case of rod promoter and the increase in disk diameter/thickness for the disk promoter is due to the increase in the effectiveness of the promoter elements in breaking the bubbles and minimizing the slug formation.

In addition, the bed fluctuation decreases with decrease in the distributor open area. This may be attributed to the formation of relatively smaller-sized bubbles generated from the orifices of smaller diameter. Also, the formation of small length spouts (at the origin) in case of smaller diameter orifices rather than long channels in the bed may be attributed to the reduction of bed fluctuation.

## 5.4 Conclusion

The bed fluctuiation is significantly influenced by the distributor, promoter and other system variables. Fig. 5.5 shows that the bed fluctuation increases with increase in fluid velocity under similar o perating conditions. From the comparison of the calculated values of bed fluctuation (Table 5.11), it has been seen that all the promoters used in the experimentation are quite effective in reducing bed fluctuation when compared to unpromoted ones. The disk and blade promoters have been found to be more effective in reducing bed fluctuation than rod promoters. In comparison to disk promoter, a blade promoter performs slightly better in reducing bed fluctuation. Also, the decrease in distributor open area results in the reduction of bed fluctuation. The effects of both distributor and promoter parameters in reducing bed fluctuation are evident for almost complete regime of fluidization. Only in the neighourhood of minimum fluidization condition (i.e. $G_R \leqslant 0.015$) where the bed dynamics appears to be not fully stabilized, distributor and promoter have little randomized affects.

The combined effect of an appropriate promoter and distributor with decreased open area results in better quality gas-solid fluidization with reduced bubble formation and slugging. This leads to reduced height of the gas-solid fluidized unit thus making the design economical.

Nomenclature

| | |
|---|---|
| $a, b, c, d, e, f, g, h$ | exponents |
| $A_c$ | cross sectional area of column , $L^2$ |
| $A_{do}$ | open area of distributor, $L^2$ |
| $A_o$ | open area in promoted bed with rod promoters, $L^2$ |
| BP | bed with blade promoter |
| $D_c$ | column diameter, L |
| $D_e$ | equivalent diameter of promoter, $4A_o / P$, L |
| $D_k$ | disk diameter, L |
| DP | bed with disk promoter |
| $d_o$ | orifice diameter, L |
| $d_p$ | particle size, L |
| $G_f$ | fluidization mass velocity, $ML^{-2}T^{-1}$ |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted bed, $ML^{-2}T^{-1}$ |
| $G'_{mf}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $G_R$ | mass velocity ratio for unpromoted beds, $(G_f - G_{mf})/(G_t - G_{mf})$ |
| | mass velocity ratio for promoted beds, $(G_f - G'_{mf})/(G_t - G'_{mf})$ |
| $G_t$ | terminal mass velocity, $ML^{-2}T^{-1}$ |
| $h_{av}$ | average height of fluidized bed, $(h_{\max} + h_{\min})/2$, L |
| $h_{\max}$ | maximum height of fluidized bed, L |
| $h_{\min}$ | minimum height of fluidized bed, L |
| $h_s$ | initial static bed height, L |
| K | constant |

| | |
|---|---|
| $m$ | slope (Eq. 5.1) |
| $P$ | total rod perimeter, L |
| $r$ | bed fluctuation ratio, $h_{\max} / h_{\min}$ |
| $r'$ | modified bed fluctuation ratio, $r-1$ |
| RP | bed with rod promoter |
| $R^2$ | coefficient of determination |
| $t$ | disk thickness, L |
| UP | unpromoted bed |
| $U_b$ | velocity of bubble, $LT^{-1}$ |
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |

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**Table 5.1** Sum squared error (SSE) for various ANN-structure tested for unpromoted bed

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I X H X O ) | Sum squared error |
| 5 2 1 | 0.084678 |
| 5 4 1 | 0.081244 |
| 5 6 1 | 0.080268 |
| 5 8 1 | 0.082293 |
| 5 9 1 | 0.080334 |
| 5 10 1 | 0.083687 |
| 5 11 1 | 0.082166 |
| 5 12 1 | 0.079916 |
| 5 13 1 | 0.082451 |
| 5 14 1 | 0.082329 |
| 5 15 1* | 0.077253 |
| 5 16 1 | 0.080689 |
| 5 17 1 | 0.079881 |
| 5 18 1 | 0.079881 |

* selected structure

**Table 5.2** Sum squared error (SSE) for various ANN-structure tested for bed with rod promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I X H X O ) | Sum squared error |
| 6 2 1 | 0.048732 |
| 6 4 1 | 0.046095 |
| 6 6 1 | 0.0422 |
| 6 8 1 | 0.045261 |
| 6 10 1 | 0.04127 |
| 6 12 1 | 0.04551 |
| 6 14 1 | 0.041888 |
| 6 16 1 | 0.040349 |
| 6 18 1 | 0.041665 |
| 6 19 1 | 0.042378 |
| 6 20 1* | 0.038939 |
| 6 21 1 | 0.039554 |
| 6 22 1 | 0.040008 |

* selected structure

**Table 5.3** Sum squared error (SSE) for various ANN-structure tested for bed with disk promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I X H X O ) | Sum squared error |
| 7 2 1 | 0.035159 |
| 7 4 1 | 0.033193 |
| 7 6 1 | 0.033364 |
| 7 8 1 | 0.033369 |
| 7 10 1 | 0.031675 |
| 7 12 1 | 0.032681 |
| 7 14 1 | 0.033532 |
| 7 16 1 | 0.03071 |
| 7 18 1 | 0.029424 |
| 7 20 1 | 0.031491 |
| 7 21 1* | 0.027645 |
| 7 22 1 | 0.026841 |
| 7 24 1 | 0.028051 |
| 7 25 1 | 0.028645 |

* selected structure

**Table 5.4** Sum squared error (SSE) for various ANN-structure tested for bed with blade promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I X H X O ) | Sum squared error |
| 5 2 1 | 0.018778 |
| 5 6 1 | 0.018606 |
| 5 8 1 | 0.021356 |
| 5 10 1 | 0.019747 |
| 5 12 1 | 0.017689 |
| 5 13 1 | 0.019329 |
| 5 15 1 | 0.019093 |
| 5 17 1 | 0.016086 |
| 5 18 1 | 0.015951 |
| 5 20 1* | 0.014116 |
| 5 21 1 | 0.014499 |
| 5 23 1 | 0.018465 |
| 5 25 1 | 0.021249 |

* selected structure

**Table 5.5** Selected structures of neural network models for test problems undertaken

| Learning rate 0.001-0.100 | | | |
|---|---|---|---|
| Bed particulars | Hidden Nodes | Output Nodes | Number of cycles used for training |
| Unpromoted bed | 14 | 1 | 50,000 |
| Bed with rod promoter | 20 | 1 | 50,000 |
| Bed with disk promoter | 22 | 1 | 50,000 |
| Bed with blade promoter | 20 | 1 | 50,000 |

**Table 5.6** Comparison between experimental and predicted (Eq. 5.5 and ANN-model) values of bed fluctuation ratio for unpromoted bed

| Serial No. | System variables | | | | | Bed fluctuation ratio ( $r$ ) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Exptl. | Predicted by | |
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | | Eq. 5.4 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 0.070 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.85 | 1.88 | 1.85 |
| 2 | 0.088 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.08 | 2.08 | 2.04 |
| 3 | 0.107 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.23 | 2.27 | 2.24 |
| 4 | 0.073 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.61 | 1.67 | 1.65 |
| 5 | 0.099 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.77 | 1.87 | 1.91 |
| 6 | 0.125 | 1409.2 | 0.09 | 0.29 | 2.36 | 2.06 | 2.05 | 2.18 |
| 7 | 0.177 | 1409.2 | 0.09 | 0.29 | 2.36 | 2.45 | 2.41 | 2.72 |
| 8 | 0.045 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.68 | 1.75 | 1.83 |
| 9 | 0.070 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.12 | 2.09 | 2.09 |
| 10 | 0.087 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.21 | 2.30 | 2.26 |
| 11 | 0.089 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.29 | 2.33 | 2.29 |
| 12 | 0.120 | 3245.8 | 0.09 | 0.29 | 2.36 | 2.75 | 2.71 | 2.61 |
| 13 | 0.013 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.32 | 1.30 | 1.72 |
| 14 | 0.020 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.54 | 1.44 | 1.79 |
| 15 | 0.065 | 4066.7 | 0.09 | 0.29 | 2.36 | 2.40 | 2.17 | 2.25 |
| 16 | 0.078 | 4066.7 | 0.09 | 0.29 | 2.36 | 2.67 | 2.37 | 2.39 |
| 17 | 0.023 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.45 | 1.37 | 1.49 |
| 18 | 0.032 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.58 | 1.50 | 1.58 |
| 19 | 0.109 | 2347.5 | 0.129 | 0.29 | 2.36 | 2.48 | 2.40 | 2.36 |
| 20 | 0.126 | 2347.5 | 0.129 | 0.29 | 2.36 | 2.6 | 2.58 | 2.55 |
| 21 | 0.079 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.88 | 1.89 | 1.86 |
| 22 | 0.088 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.97 | 1.98 | 1.96 |
| 23 | 0.097 | 2347.5 | 0.057 | 0.29 | 2.36 | 2.01 | 2.07 | 2.05 |
| 24 | 0.109 | 2347.5 | 0.057 | 0.29 | 2.36 | 2.15 | 2.18 | 2.17 |
| 25 | 0.052 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.58 | 1.57 | 1.55 |
| 26 | 0.063 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.67 | 1.68 | 1.66 |
| 27 | 0.086 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.89 | 1.88 | 1.89 |
| 28 | 0.051 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.59 | 1.54 | 1.53 |

**Continued on next page**

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 29 | 0.126 | 2347.5 | 0.032 | 0.29 | 2.36 | 2.25 | 2.18 | 2.29 |
| 30 | 0.014 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.14 | 1.15 | 1.17 |
| 31 | 0.023 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.22 | 1.23 | 1.24 |
| 32 | 0.032 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.32 | 1.31 | 1.32 |
| 33 | 0.042 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.43 | 1.39 | 1.40 |
| 34 | 0.070 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.69 | 1.60 | 1.66 |
| 35 | 0.034 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.48 | 1.57 | 1.68 |
| 36 | 0.042 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.64 | 1.69 | 1.76 |
| 37 | 0.154 | 2347.5 | 0.09 | 0.185 | 2.36 | 2.69 | 2.44 | 2.60 |
| 38 | 0.044 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.38 | 1.47 | 1.45 |
| 39 | 0.057 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.56 | 1.58 | 1.56 |
| 40 | 0.132 | 2347.5 | 0.09 | 0.156 | 2.36 | 2.39 | 2.18 | 2.33 |
| 41 | 0.157 | 2347.5 | 0.09 | 0.156 | 2.36 | 2.56 | 2.37 | 2.59 |
| 42 | 0.182 | 2347.5 | 0.09 | 0.156 | 2.36 | 2.82 | 2.55 | 2.85 |
| 43 | 0.207 | 2347.5 | 0.09 | 0.156 | 2.36 | 2.87 | 2.73 | 3.1 |
| 44 | 0.033 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.23 | 1.34 | 1.32 |
| 45 | 0.047 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.34 | 1.46 | 1.45 |
| 46 | 0.061 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.47 | 1.57 | 1.58 |
| 47 | 0.131 | 2347.5 | 0.09 | 0.131 | 2.36 | 2.07 | 2.09 | 2.29 |
| 48 | 0.159 | 2347.5 | 0.09 | 0.131 | 2.36 | 2.38 | 2.29 | 2.59 |
| 49 | 0.187 | 2347.5 | 0.09 | 0.131 | 2.36 | 2.61 | 2.48 | 2.87 |
| 50 | 0.216 | 2347.5 | 0.09 | 0.131 | 2.36 | 2.68 | 2.66 | 3.15 |
| 51 | 0.023 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.38 | 1.40 | 1.49 |
| 52 | 0.079 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.08 | 2.13 | 2.05 |
| 53 | 0.088 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.14 | 2.25 | 2.14 |
| 54 | 0.097 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.27 | 2.36 | 2.24 |
| 55 | 0.107 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.39 | 2.47 | 2.34 |
| 56 | 0.109 | 2347.5 | 0.09 | 0.29 | 1.58 | 2.47 | 2.50 | 2.37 |
| 57 | 0.042 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.49 | 1.51 | 1.48 |
| 58 | 0.051 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.57 | 1.61 | 1.56 |
| 59 | 0.070 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.73 | 1.79 | 1.74 |
| 60 | 0.088 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.97 | 1.97 | 1.93 |
| 61 | 0.109 | 2347.5 | 0.09 | 0.29 | 3.15 | 2.16 | 2.17 | 2.15 |
| 62 | 0.023 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.25 | 1.29 | 1.22 |
| 63 | 0.070 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.69 | 1.73 | 1.64 |
| 64 | 0.088 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.92 | 1.90 | 1.82 |
| 65 | 0.144 | 2347.5 | 0.09 | 0.29 | 3.94 | 2.25 | 2.36 | 2.40 |

**Table 5.7** Comparison between experimental and calculated (Eq. 5.6 and ANN-model) values of bed fluctuation ratio for bed with rod promoter

| Serial No. | System variables | | | | | | Bed fluctuation ratio ( $r$ ) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Exptl. | Predicted by | |
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | $D_e / D_c$ | | Eq. 5.6 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 1 | 0.043 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 1.35 | 1.36 | 1.36 |
| 2 | 0.099 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 1.60 | 1.65 | 1.65 |
| 3 | 0.102 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 1.66 | 1.66 | 1.66 |
| 4 | 0.119 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 1.71 | 1.73 | 1.75 |
| 5 | 0.026 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 1.22 | 1.30 | 1.31 |
| 6 | 0.035 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 1.32 | 1.37 | 1.36 |
| 7 | 0.045 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 1.47 | 1.44 | 1.41 |
| 8 | 0.060 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.43 | 1.41 | 1.38 |
| 9 | 0.069 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.44 | 1.46 | 1.42 |
| 10 | 0.079 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.46 | 1.50 | 1.46 |
| 11 | 0.117 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 1.63 | 1.66 | 1.63 |
| 12 | 0.040 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.22 | 1.29 | 1.23 |
| 13 | 0.058 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.32 | 1.38 | 1.32 |
| 14 | 0.068 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 1.34 | 1.42 | 1.36 |
| 15 | 0.042 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.18 | 1.28 | 1.22 |
| 16 | 0.055 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.28 | 1.33 | 1.27 |
| 17 | 0.068 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.32 | 1.39 | 1.33 |
| 18 | 0.201 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.76 | 1.82 | 1.76 |
| 19 | 0.249 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 1.85 | 1.95 | 1.82 |
| 20 | 0.037 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.29 | 1.38 | 1.42 |
| 21 | 0.045 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.37 | 1.44 | 1.46 |
| 22 | 0.081 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.60 | 1.66 | 1.67 |
| 23 | 0.112 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 1.70 | 1.83 | 1.84 |
| 24 | 0.025 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 1.38 | 1.33 | 1.39 |
| 25 | 0.039 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 1.43 | 1.45 | 1.48 |
| 26 | 0.041 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 1.58 | 1.46 | 1.49 |
| 27 | 0.080 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.248 | 1.65 | 1.59 | 1.61 |
| 28 | 0.099 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.248 | 1.70 | 1.68 | 1.70 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|
| 29 | 0.102 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.248 | 1.75 | 1.69 | 1.71 |
| 30 | 0.062 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.47 | 1.44 | 1.42 |
| 31 | 0.080 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.50 | 1.53 | 1.52 |
| 32 | 0.099 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.63 | 1.61 | 1.61 |
| 33 | 0.103 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 1.72 | 1.62 | 1.62 |
| 34 | 0.102 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.62 | 1.57 | 1.59 |
| 35 | 0.119 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.65 | 1.64 | 1.68 |
| 36 | 0.136 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.76 | 1.70 | 1.75 |
| 37 | 0.154 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 1.80 | 1.76 | 1.82 |
| 38 | 0.033 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.248 | 1.25 | 1.24 | 1.23 |
| 39 | 0.071 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.248 | 1.43 | 1.40 | 1.42 |
| 40 | 0.080 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.248 | 1.46 | 1.44 | 1.47 |
| 41 | 0.038 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.248 | 1.34 | 1.37 | 1.33 |
| 42 | 0.041 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.248 | 1.44 | 1.39 | 1.34 |
| 43 | 0.056 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.248 | 1.46 | 1.49 | 1.43 |
| 44 | 0.058 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.44 | 1.40 | 1.37 |
| 45 | 0.069 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.48 | 1.45 | 1.42 |
| 46 | 0.161 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.73 | 1.81 | 1.76 |
| 47 | 0.173 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.78 | 1.85 | 1.79 |
| 4 8 | 0.218 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 1.83 | 2.00 | 1.87 |
| 49 | 0.041 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 1.21 | 1.29 | 1.26 |
| 50 | 0.078 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 1.44 | 1.47 | 1.42 |
| 51 | 0.103 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 1.54 | 1.57 | 1.52 |
| 52 | 0.043 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 1.49 | 1.42 | 1.40 |
| 53 | 0.052 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 1.53 | 1.48 | 1.45 |
| 54 | 0.062 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 1.58 | 1.54 | 1.50 |
| 55 | 0.154 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 1.94 | 2.02 | 2.01 |
| 56 | 0.171 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 2.02 | 2.10 | 2.09 |
| 57 | 0.043 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.37 | 1.32 | 1.35 |
| 58 | 0.071 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.49 | 1.46 | 1.48 |
| 59 | 0.080 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.52 | 1.50 | 1.52 |
| 60 | 0.171 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.8 | 1.84 | 1.81 |
| 61 | 0.206 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 1.85 | 1.96 | 1.87 |
| 62 | 0.099 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 1.55 | 1.53 | 1.52 |
| 63 | 0.102 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 1.57 | 1.54 | 1.53 |
| 64 | 0.136 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 1.65 | 1.66 | 1.61 |
| 65 | 0.171 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 1.73 | 1.77 | 1.66 |

**Table 5.8** Comparison between experimental and calculated (Eq. 5.7 and ANN- model) values of bed fluctuation ratio for bed with disk promoter

| Serial No. | System variables | | | | | | | Bed fluctuation ratio ( $r$ ) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Exptl. | Predicted by | |
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | $t / D_c$ | $D_k / D_c$ | | Eq. 5.7 | ANN-Model |
| 1 | 0.095 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.58 | 1.57 | 1.61 |
| 2 | 0.104 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.62 | 1.60 | 1.64 |
| 3 | 0.107 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.64 | 1.61 | 1.65 |
| 4 | 0.026 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.28 | 1.31 | 1.35 |
| 5 | 0.104 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.73 | 1.70 | 1.70 |
| 6 | 0.121 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.76 | 1.78 | 1.76 |
| 7 | 0.138 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 1.80 | 1.85 | 1.82 |
| 8 | 0.125 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 1.64 | 1.62 | 1.66 |
| 9 | 0.142 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 1.71 | 1.68 | 1.72 |
| 10 | 0.159 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 1.73 | 1.75 | 1.77 |
| 11 | 0.106 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 1.52 | 1.53 | 1.54 |
| 12 | 0.108 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 1.56 | 1.53 | 1.55 |
| 13 | 0.061 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 1.54 | 1.53 | 1.55 |
| 14 | 0.153 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 1.97 | 1.88 | 1.97 |
| 15 | 0.022 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.15 | 1.19 | 1.23 |
| 16 | 0.031 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.22 | 1.24 | 1.27 |
| 17 | 0.160 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.63 | 1.70 | 1.71 |
| 18 | 0.177 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 1.67 | 1.76 | 1.75 |
| 19 | 0.108 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.770 | 1.50 | 1.48 | 1.49 |
| 20 | 0.046 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.21 | 1.28 | 1.21 |
| 21 | 0.059 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.24 | 1.33 | 1.26 |
| 22 | 0.188 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.64 | 1.71 | 1.65 |
| 23 | 0.201 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.64 | 1.74 | 1.68 |
| 24 | 0.117 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.78 | 1.72 | 1.80 |
| 25 | 0.148 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.82 | 1.89 | 1.90 |
| 26 | 0.165 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.86 | 1.95 | 1.96 |
| 27 | 0.032 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.35 | 1.43 | 1.44 |
| 28 | 0.088 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 1.71 | 1.69 | 1.71 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 29 | 0.086 | 2347.5 | 0.129 | 0.29 | 2.36 | 0.125 | 0.551 | 1.72 | 1.56 | 1.67 |
| 30 | 0.095 | 2347.5 | 0.129 | 0.29 | 2.36 | 0.125 | 0.551 | 1.77 | 1.60 | 1.71 |
| 31 | 0.086 | 2347.5 | 0.129 | 0.29 | 2.36 | 0.125 | 0.551 | 1.52 | 1.50 | 1.49 |
| 32 | 0.095 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 1.53 | 1.53 | 1.53 |
| 33 | 0.100 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 1.53 | 1.53 | 1.53 |
| 34 | 0.176 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 1.80 | 1.81 | 1.79 |
| 35 | 0.067 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 1.41 | 1.39 | 1.35 |
| 36 | 0.095 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 1.49 | 1.48 | 1.47 |
| 37 | 0.020 | 2347.5 | 0.014 | 0.29 | 2.36 | 0.125 | 0.551 | 1.08 | 1.16 | 1.11 |
| 38 | 0.030 | 2347.5 | 0.014 | 0.29 | 2.36 | 0.125 | 0.551 | 1.15 | 1.20 | 1.15 |
| 39 | 0.141 | 2347.5 | 0.014 | 0.29 | 2.36 | 0.125 | 0.551 | 1.57 | 1.62 | 1.58 |
| 40 | 0.158 | 2347.5 | 0.014 | 0.29 | 2.36 | 0.1257 | 0.551 | 1.64 | 1.62 | 1.63 |
| 41 | 0.049 | 2347.5 | 0.09 | 0.45 | 2.36 | 0.125 | 0.551 | 1.47 | 1.40 | 1.36 |
| 42 | 0.064 | 2347.5 | 0.09 | 0.45 | 2.36 | 0.125 | 0.551 | 1.50 | 1.48 | 1.44 |
| 43 | 0.079 | 2347.5 | 0.09 | 0.45 | 2.36 | 0.125 | 0.551 | 1.58 | 1.56 | 1.51 |
| 44 | 0.094 | 2347.5 | 0.09 | 0.45 | 2.36 | 0.125 | 0.551 | 1.62 | 1.63 | 1.58 |
| 45 | 0.096 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 1.56 | 1.51 | 1.55 |
| 46 | 0.107 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 1.61 | 1.55 | 1.59 |
| 47 | 0.176 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 1.77 | 1.78 | 1.76 |
| 48 | 0.043 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 1.33 | 1.29 | 1.32 |
| 49 | 0.055 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 1.40 | 1.34 | 1.37 |
| 50 | 0.081 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 1.50 | 1.44 | 1.47 |
| 51 | 0.106 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 1.58 | 1.52 | 1.55 |
| 52 | 0.088 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.50 | 1.45 | 1.46 |
| 53 | 0.102 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.55 | 1.49 | 1.50 |
| 54 | 0.215 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.74 | 1.81 | 1.73 |
| 55 | 0.229 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 1.77 | 1.84 | 1.74 |
| 56 | 0.048 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.48 | 1.43 | 1.46 |
| 57 | 0.104 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.67 | 1.73 | 1.71 |
| 58 | 0.107 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.71 | 1.74 | 1.72 |
| 59 | 0.141 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.84 | 1.89 | 1.85 |
| 60 | 0.158 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 1.88 | 1.96 | 1.91 |
| 61 | 0.176 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 2.00 | 1.95 | 1.96 |
| 62 | 0.076 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 1.46 | 1.43 | 1.47 |
| 63 | 0.141 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 1.65 | 1.71 | 1.70 |
| 64 | 0.067 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 1.34 | 1.35 | 1.37 |
| 65 | 0.141 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 1.58 | 1.63 | 1.62 |

**Table 5.9** Comparison between experimental and calculated (Eq. 5.8 and ANN-model) values of bed fluctuation ratio for bed with blade promoter

| Serial No. | System variables | | | | | Bed fluctuation ratio ( $r$ ) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Exptl. | Predicted by | |
| | $G_R$ | $\rho_s / \rho_f$ | $A_{do} / A$ | $d_p / d_o$ | $h_s / D_c$ | | Eq. 5.8 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 0.062 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.30 | 1.30 | 1.34 |
| 2 | 0.100 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.40 | 1.38 | 1.40 |
| 3 | 0.102 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.41 | 1.39 | 1.41 |
| 4 | 0.120 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.45 | 1.42 | 1.44 |
| 5 | 0.031 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.15 | 1.18 | 1.20 |
| 6 | 0.044 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.17 | 1.21 | 1.22 |
| 7 | 0.096 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.33 | 1.32 | 1.30 |
| 8 | 0.122 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.34 | 1.36 | 1.34 |
| 9 | 0.135 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.35 | 1.38 | 1.35 |
| 10 | 0.148 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.42 | 1.39 | 1.37 |
| 11 | 0.203 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.46 | 1.46 | 1.45 |
| 12 | 0.063 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.34 | 1.33 | 1.37 |
| 13 | 0.079 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.39 | 1.38 | 1.41 |
| 14 | 0.082 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.41 | 1.38 | 1.41 |
| 15 | 0.113 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.46 | 1.45 | 1.48 |
| 16 | 0.128 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.47 | 1.48 | 1.51 |
| 17 | 0.051 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.35 | 1.33 | 1.35 |
| 18 | 0.060 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.37 | 1.35 | 1.37 |
| 19 | 0.062 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.40 | 1.36 | 1.38 |
| 20 | 0.044 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.31 | 1.26 | 1.35 |
| 21 | 0.091 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.42 | 1.38 | 1.43 |
| 22 | 0.120 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.51 | 1.44 | 1.49 |
| 23 | 0.154 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.59 | 1.50 | 1.55 |
| 24 | 0.172 | 2347.5 | 0.129 | 0.29 | 2.36 | 1.62 | 1.53 | 1.58 |
| 25 | 0.072 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.33 | 1.30 | 1.31 |
| 26 | 0.102 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.38 | 1.36 | 1.37 |
| 27 | 0.120 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.40 | 1.39 | 1.40 |
| 28 | 0.154 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.43 | 1.45 | 1.46 |

**Continued on next page**

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 29 | 0.072 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.31 | 1.28 | 1.28 |
| 30 | 0.091 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.33 | 1.32 | 1.32 |
| 31 | 0.120 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.37 | 1.37 | 1.37 |
| 32 | 0.137 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.39 | 1.39 | 1.40 |
| 33 | 0.044 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.23 | 1.20 | 1.21 |
| 34 | 0.072 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.27 | 1.25 | 1.26 |
| 35 | 0.102 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.31 | 1.30 | 1.32 |
| 36 | 0.120 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.34 | 1.33 | 1.35 |
| 37 | 0.137 | 2347.5 | 0.014 | 0.29 | 2.36 | 1.41 | 1.35 | 1.37 |
| 38 | 0.078 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.39 | 1.36 | 1.39 |
| 39 | 0.093 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.45 | 1.40 | 1.42 |
| 40 | 0.108 | 2347.5 | 0.09 | 0.45 | 2.36 | 1.49 | 1.43 | 1.46 |
| 41 | 0.107 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.41 | 1.36 | 1.35 |
| 42 | 0.118 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.41 | 1.38 | 1.37 |
| 43 | 0.164 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.45 | 1.45 | 1.43 |
| 44 | 0.176 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.46 | 1.47 | 1.45 |
| 45 | 0.041 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.25 | 1.22 | 1.23 |
| 46 | 0.054 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.27 | 1.25 | 1.25 |
| 47 | 0.079 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.32 | 1.30 | 1.29 |
| 48 | 0.154 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.39 | 1.43 | 1.39 |
| 49 | 0.231 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.45 | 1.52 | 1.48 |
| 50 | 0.254 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.48 | 1.55 | 1.51 |
| 51 | 0.059 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.25 | 1.25 | 1.24 |
| 52 | 0.073 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.3 | 1.28 | 1.26 |
| 53 | 0.129 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.34 | 1.38 | 1.33 |
| 54 | 0.185 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.37 | 1.45 | 1.39 |
| 55 | 0.025 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.28 | 1.25 | 1.35 |
| 56 | 0.081 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.32 | 1.45 | 1.46 |
| 57 | 0.120 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.43 | 1.55 | 1.53 |
| 58 | 0.137 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.68 | 1.59 | 1.56 |
| 59 | 0.072 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.21 | 1.27 | 1.27 |
| 60 | 0.120 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.42 | 1.35 | 1.35 |
| 61 | 0.137 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.47 | 1.37 | 1.38 |
| 62 | 0.172 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.52 | 1.41 | 1.44 |
| 63 | 0.044 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.13 | 1.18 | 1.15 |
| 64 | 0.100 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.26 | 1.27 | 1.24 |
| 65 | 0.120 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.27 | 1.30 | 1.27 |

**Table 5.10** Mean and standard deviations

| Bed particulars | Standard deviation | | Mean | | No. of data |
|---|---|---|---|---|---|
| | Dimensional Analysis Method | ANN-Model | Dimensional Analysis Method | ANN-Model | |
| UP | 2.02 | 0.27 | 3.31 | 3.60 | 158 |
| RP | 2.20 | 2.71 | 3.15 | 2.18 | 191 |
| DP | 3.34 | 2.74 | 2.58 | 1.98 | 249 |
| BP | 1.72 | 2.80 | 2.35 | 1.86 | 154 |

**Table 5.11** Comparison between calculated (Eqs.5.5-5.8) values of bed fluctuation ratio for unpromoted bed and beds with rod, disk and blade promoters

| Sl. No | Variables | Constants: $\rho_s / \rho_f$ =2347.5, $A_{do} / A_c$ =0.09, $d_p / d_o$ =0.29, $h_s / D_c$ =2.36, $D_e / D_c$ =1.248, $t / D_c$ =0.125, $D_k / D_c$ =0.551 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $G_R$ | Predicted values of bed fluctuation ratio, r | | | | % reduction in r over unpromoted bed | | |
| | | UP | RP | DP | BP | RP | DP | BP |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 0.02 | 1.31 | 1.21 | 1.20 | 1.17 | 7.00 | 8.12 | 10.54 |
| 2 | 0.05 | 1.67 | 1.40 | 1.37 | 1.27 | 15.77 | 17.84 | 23.88 |
| 3 | 0.08 | 1.99 | 1.56 | 1.51 | 1.34 | 21.85 | 24.47 | 32.72 |
| 4 | 0.10 | 2.20 | 1.65 | 1.59 | 1.38 | 24.99 | 27.89 | 37.20 |
| 5 | 0.12 | 2.40 | 1.74 | 1.66 | 1.42 | 27.65 | 30.75 | 40.91 |
| 6 | 0.15 | 2.70 | 1.86 | 1.77 | 1.47 | 30.95 | 34.31 | 45.46 |
| 7 | 0.20 | 3.16 | 2.05 | 1.93 | 1.54 | 35.22 | 38.88 | 51.20 |
| 8 | 0.25 | 3.62 | 2.22 | 2.09 | 1.61 | 38.49 | 42.35 | 55.49 |
| | $\rho_s / \rho_f$ | Constants: $G_R$ =0.1, $A_{do} / A_c$ =0.09, $d_p / d_o$ =0.29, $h_s / D_c$ =2.36, $D_e / D_c$ =1.248, $t / D_c$ =0.125, $D_k / D_c$ =0.551 | | | | | | |
| 9 | 1409.17 | 1.87 | 1.50 | 1.46 | 1.32 | 19.59 | 21.74 | 29.28 |
| 10 | 3245.83 | 2.47 | 1.77 | 1.68 | 1.43 | 28.61 | 31.10 | 42.36 |
| 11 | 4066.67 | 2.70 | 1.86 | 1.76 | 1.46 | 31.18 | 34.91 | 45.95 |

Continued on next page

| (1) | (2) | | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| | $A_{do} / A_c$ | | Constants: $G_R$=0.1, $\rho_s / \rho_f$=2347.5, $d_p / d_o$=0.29, $h_s / D_c$=2.36, $D_e / D_c$=1.248, $t / D_c$=0.125, $D_k / D_c$=0.551 | | | | | | |
| 12 | 0.129 | | 2.30 | 1.68 | 1.62 | 1.40 | 26.72 | 29.53 | 38.98 |
| 13 | 0.057 | | 2.09 | 1.61 | 1.55 | 1.36 | 22.85 | 25.84 | 34.95 |
| 14 | 0.032 | | 1.97 | 1.57 | 1.51 | 1.33 | 20.21 | 23.31 | 32.16 |
| 15 | 0.014 | | 1.81 | 1.51 | 1.45 | 1.30 | 16.63 | 19.86 | 28.27 |
| | $d_p / d_o$ | | Constants: $G_R$=0.1, $\rho_s / \rho_f$=2347.5, $A_{do} / A_c$=0.09, $h_s / D_c$=2.36, $D_e / D_c$=1.248, $t / D_c$=0.125, $D_k / D_c$=0.551 | | | | | | |
| 16 | 0.45 | | 2.44 | 1.73 | 1.65 | 1.41 | 29.19 | 32.22 | 42.01 |
| 17 | 0.185 | | 2.00 | 1.58 | 1.53 | 1.35 | 20.87 | 23.60 | 32.33 |
| 18 | 0.156 | | 1.93 | 1.56 | 1.51 | 1.34 | 19.36 | 22.02 | 30.52 |
| 19 | 0.131 | | 1.87 | 1.53 | 1.49 | 1.33 | 17.86 | 20.45 | 28.69 |
| | $h_s / D_c$ | | Constants: $G_R$=0.1, $\rho_s / \rho_f$=2347.5, $A_{do} / A_c$=0.09, $d_p / d_o$=0.29, $D_e / D_c$=1.248, $t / D_c$=0.125, $D_k / D_c$=0.551 | | | | | | |
| 20 | 1.58 | | 2.39 | 1.76 | 1.71 | 1.50 | 26.37 | 28.54 | 37.17 |
| 21 | 3.15 | | 2.08 | 1.58 | 1.51 | 1.32 | 23.97 | 27.29 | 36.85 |
| 22 | 3.94 | | 2.00 | 1.53 | 1.46 | 1.27 | 23.16 | 26.75 | 36.40 |
| | $D_e / D_c$ | $t / D_c$ | Constants: $G_R$=0.1, $\rho_s / \rho_f$=2347.5, $A_{do} / A_c$=0.09, $d_p / d_o$=0.29, $h_s / D_c$=2.36, $D_k / D_c$=0.551 | | | | | | |
| 23 | 2.209 | 0.063 | 2.20 | 1.76 | 1.69 | — | 20.07 | 23.28 | — |
| 24 | 0.856 | 0.188 | 2.20 | 1.59 | 1.54 | — | 27.86 | 30.26 | — |
| 25 | 0.642 | 0.250 | 2.20 | 1.54 | 1.50 | — | 29.85 | 31.82 | — |
| | $D_e / D_c$ | $D_k / D_c$ | Constants: $G_R$=0.1, $\rho_s / \rho_f$=2347.5, $A_{do} / A_c$=0.09, $d_p / d_o$=0.29, $h_s / D_c$=2.36, $t / D_c$=0.125 | | | | | | |
| 26 | 2.209 | 0.398 | 2.20 | 1.76 | 1.73 | — | 20.07 | 21.36 | — |
| 27 | 0.856 | 0.669 | 2.20 | 1.59 | 1.52 | — | 27.86 | 31.14 | — |
| 28 | 0.642 | 0.770 | 2.20 | 1.54 | 1.47 | — | 29.85 | 33.24 | — |

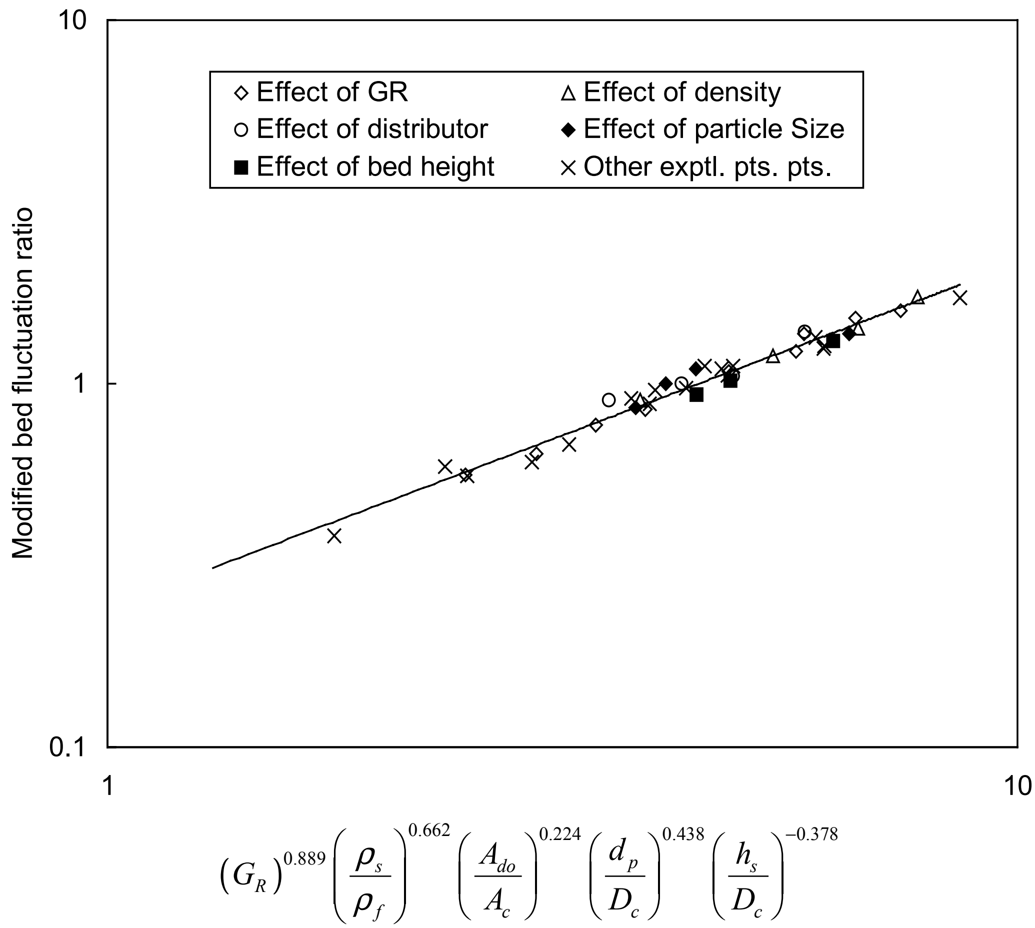
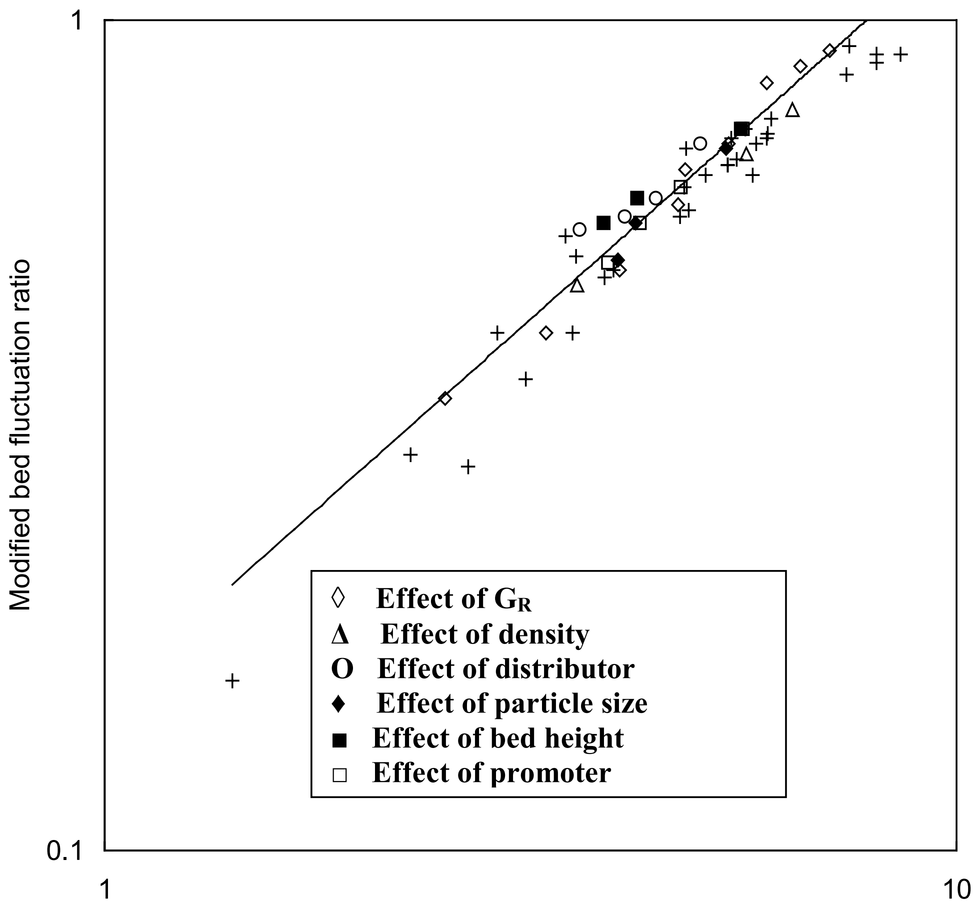



**Fig. 5.1** Variation of modified bed fluctuation ratio $\left(r'\right)$ with system parameters for unpromoted bed




$$\left(G_R\right)^{0.752}\left(\frac{\rho_s}{\rho_f}\right)^{0.550}\left(\frac{A_{do}}{A_c}\right)^{0.147}\left(\frac{d_p}{D_c}\right)^{0.275}\left(\frac{h_s}{D_c}\right)^{-0.408}\left(\frac{D_e}{D_c}\right)^{0.295}$$

**Fig. 5.2** Variation of modified bed fluctuation ratio $\left(r^{'}\right)$ with system parameters for bed with rod promoter

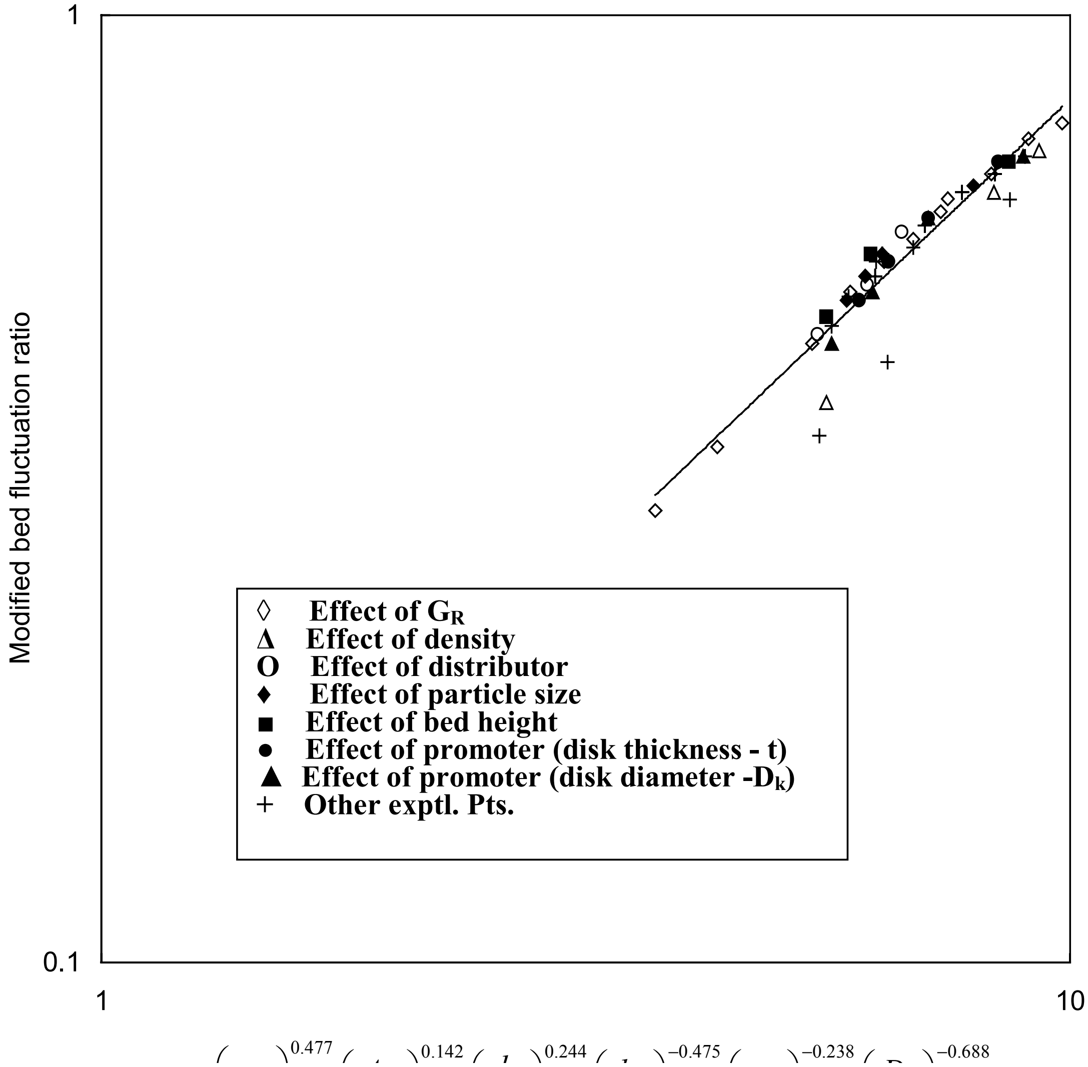



**Fig. 5.3** Variation of modified bed fluctuation ratio $\left(r'\right)$ with system parameters for bed with disk promoter

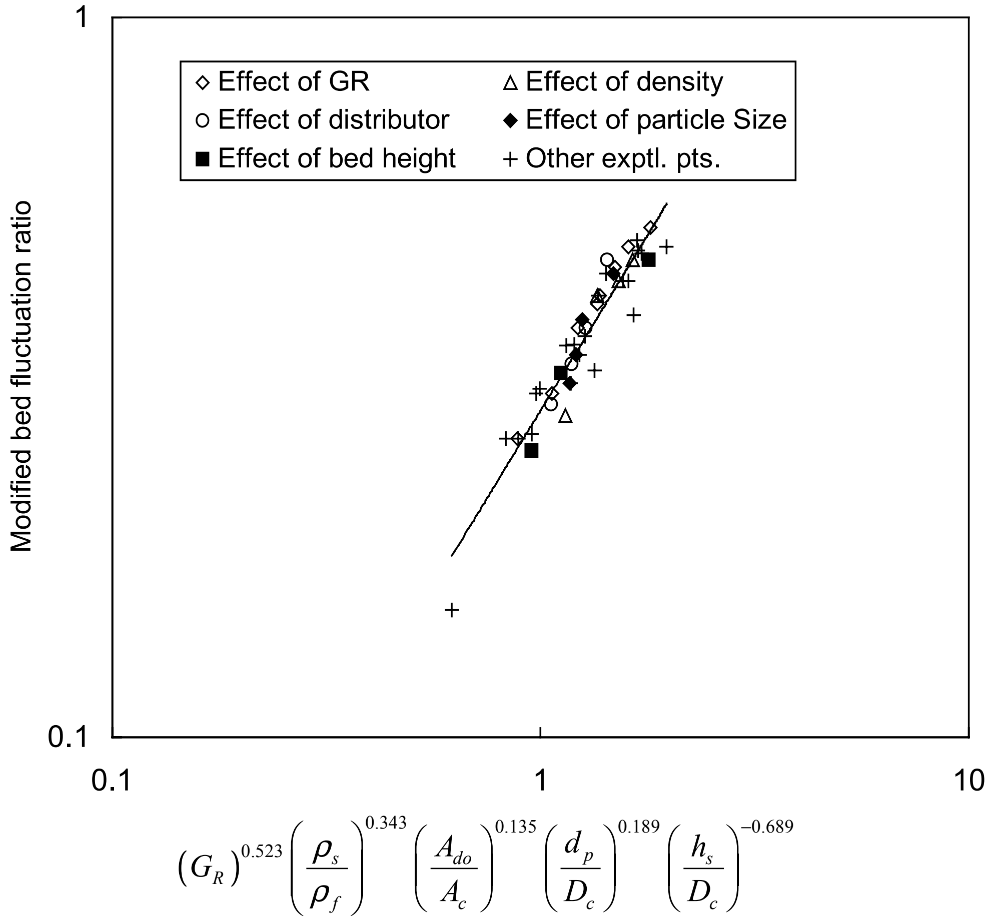



**Fig. 5.4** Variation of modified bed fluctuation ratio $\left(r'\right)$ with system parameters for bed with blade promote

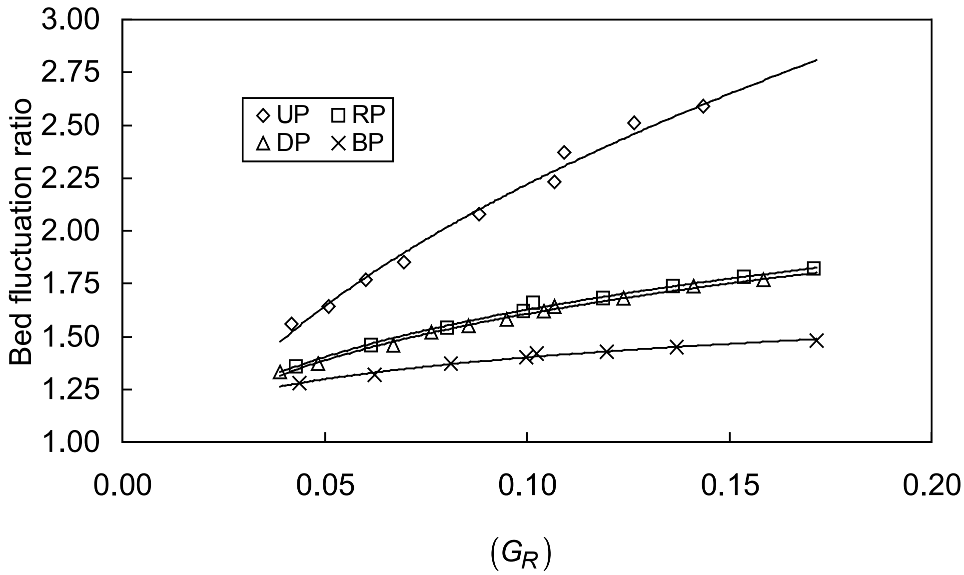



**Fig. 5.5** Variation of bed fluctuation ratio ( r ) with flow parameter ($G_R$) for different beds

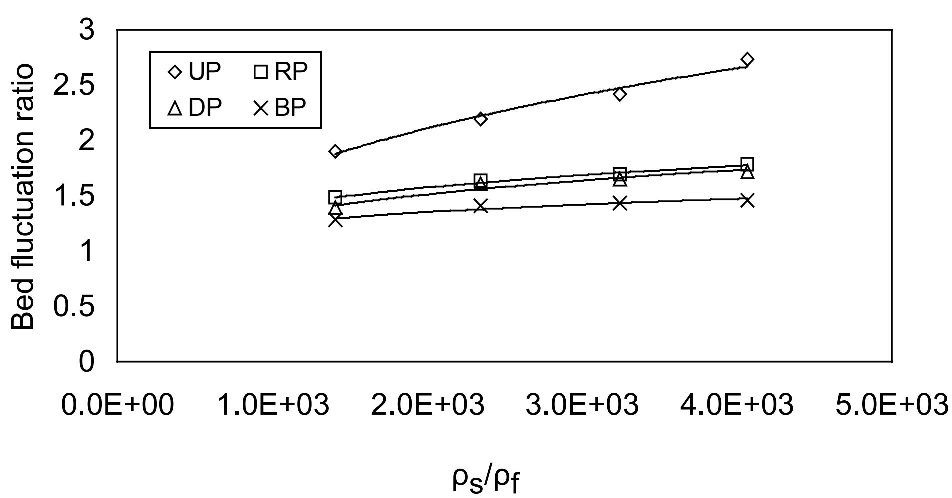



**Fig. 5.6** Variation of bed fluctuation ratio ( r ) with density parameter (ρs/ρf) for different beds

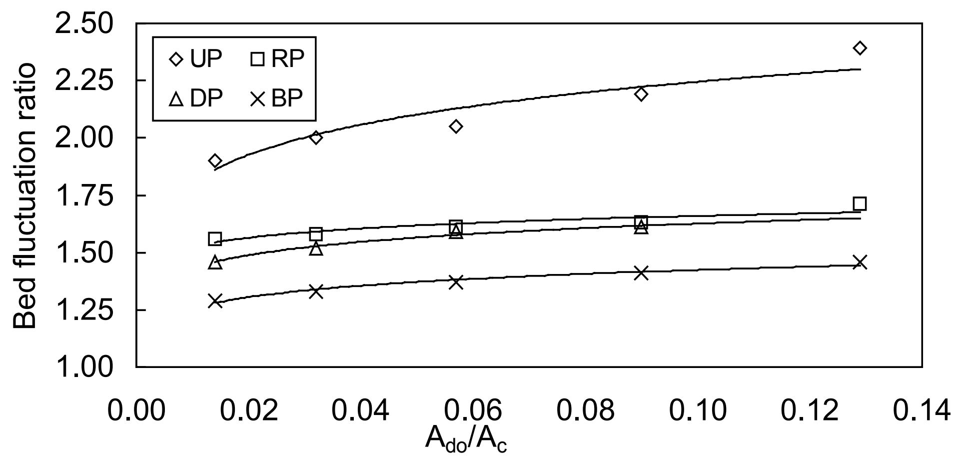



**Fig. 5.7** Variation of bed fluctuation ratio ( $r$ ) with distributor parameter ($A_{do}/A_c$) for different beds

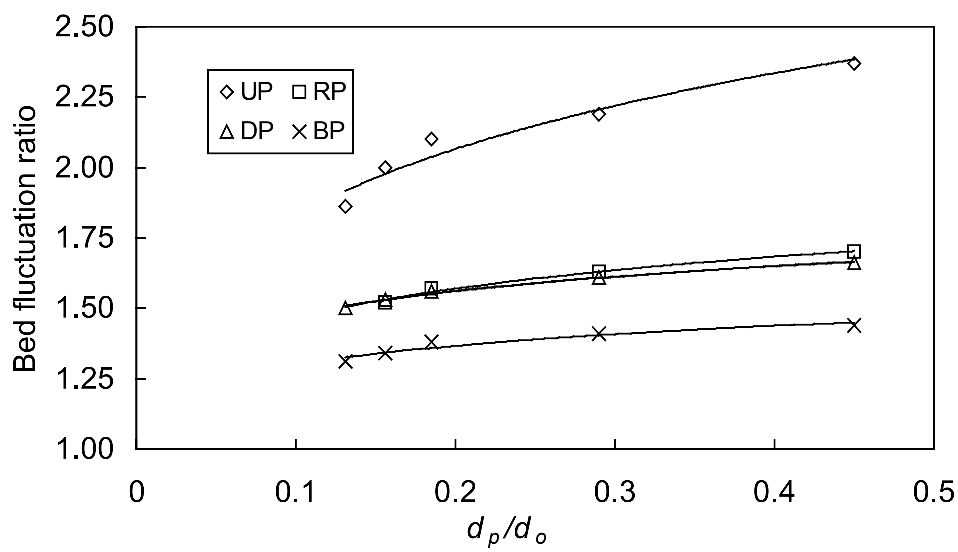



**Fig. 5.8** Variation of bed fluctuation ratio ( $r$ ) with size parameter
($d_p/d_o$) for different beds

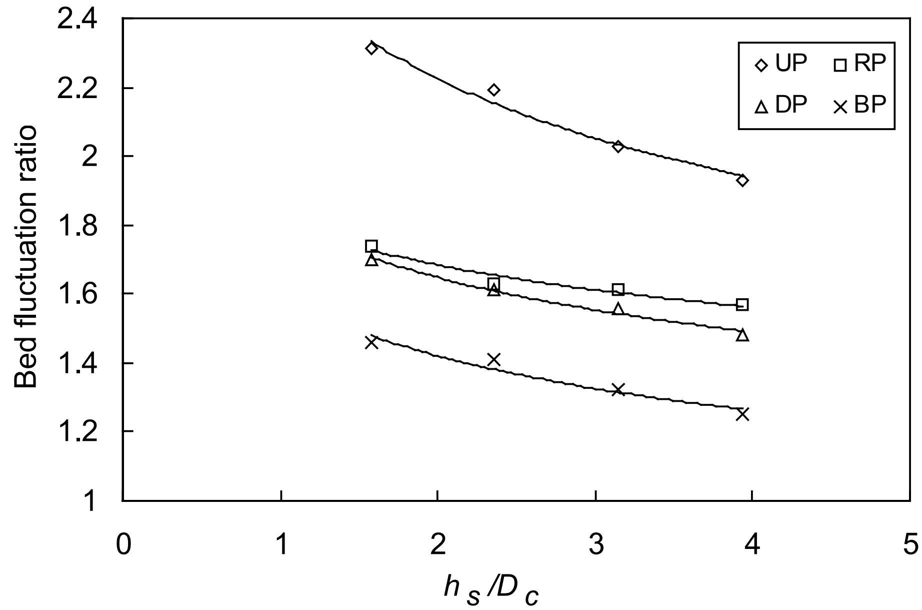



**Fig. 5.9** Variation of bed fluctuation ratio ( r ) with bed height parameter ($h_s/D_c$) for different beds

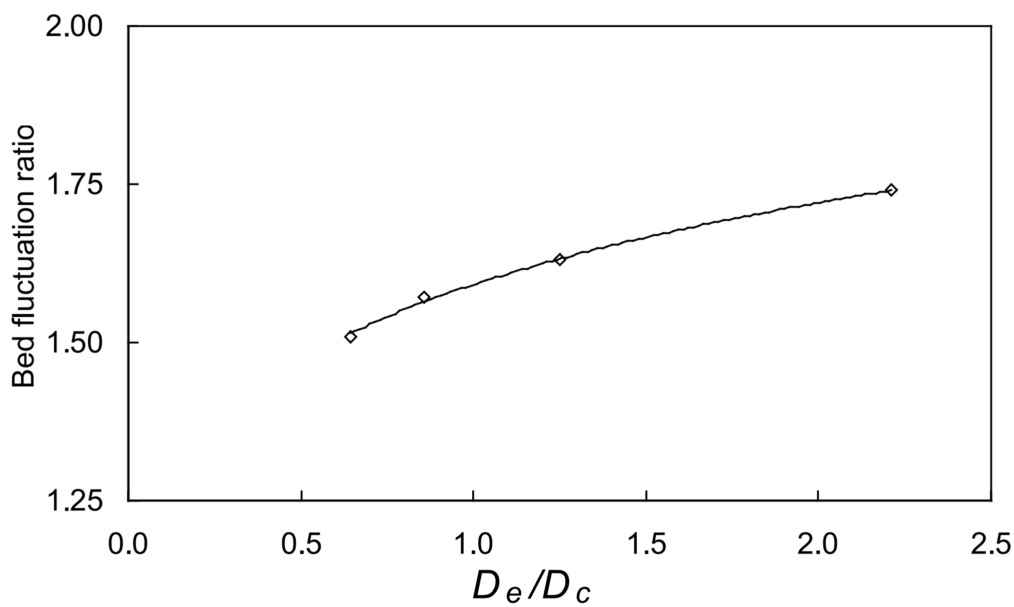



**Fig. 5.10** Variation of bed fluctuation ratio ( r ) with rod promoter parameter ($D_e/D_c$)

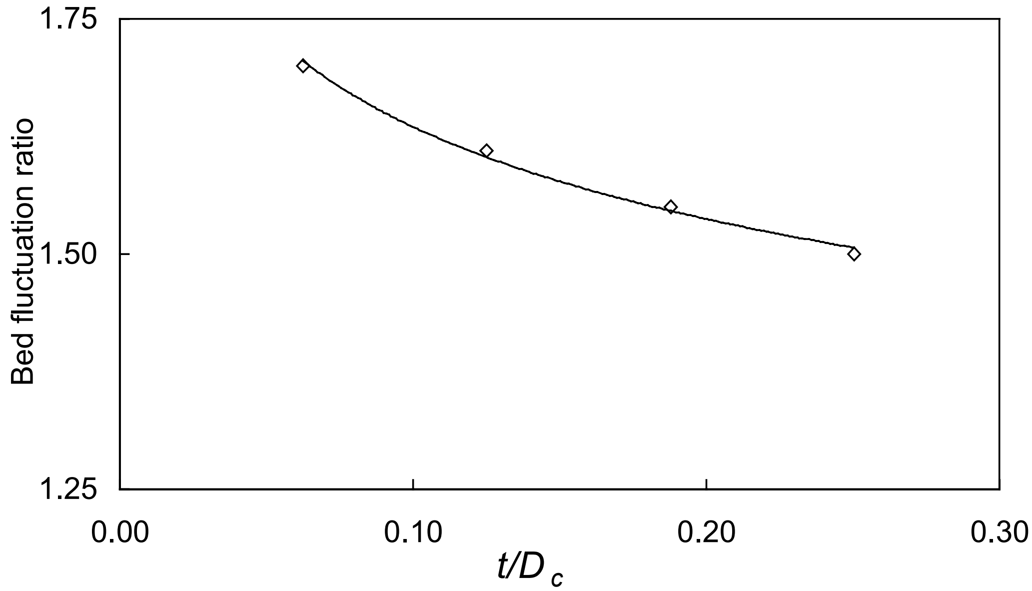



**Fig. 5.11** Variation of bed fluctuation ratio ( r ) with disk thickness parameter ($t/D_c$) for bed with disk promoter

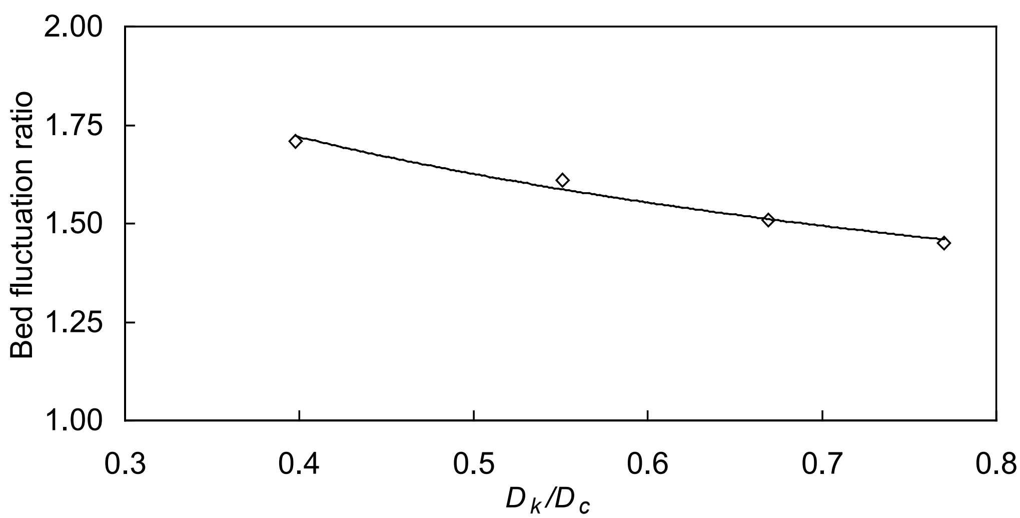



**Fig. 5.12** Variation of bed fluctuation ratio ( r ) with disk diameter parameter ($D_k/D_c$) for bed with disk promoter

# CHAPTER VI

# Prediction of pressure drop in fluidized bed promoted with rod, disk and blade type promoters

## 6.1 Introduction

The variation of pressure drop is normally linear with gas velocity in the fixed bed region [1-3]. For the relatively low flow rates in the packed bed, the pressure drop is approximately proportional to gas velocity, usually reaching a maximum value $(\Delta p_{\max})$ slightly higher than the static pressure of the bed. With a further increase in gas velocity, the packed bed suddenly unlocks (at the onset of minimum fluidization condition), resulting in a decrease in pressure drop to the static pressure of the bed. With gas velocities beyond minimum fluidization, the bed expands and gas bubbles are seen to rise with resulting nonhomogeneity in the bed. Despite this increase in gas flow, the pressure drop should remain unchanged but due to bubbling and slugging there is always fluctuation in pressure drop, resulting in slight increase with flow rate [3]. At a very high velocity, the particles will be transported from the system along with the fluid stream.

Much work have been reported since the 1950's on the flow of fluid-solid mixture. Some of these information about the pressure drop have been considered in the work of Leva [1], Zenz and Othmer [2], Davidson and Harrison [4] and Richardson and Zaki [5]. In spite of this, a knowledge of the details of the flow pattern and the prediction of pressure drop in vertical flow of fluid-solid mixture is limited. Most of the useful correlations are empirical and are based on small spherical particles which result in poor accuracy when applied to system other than the ones for which they have been developed.

When a fluid flows through a bed of solid particles, the transfer of energy takes place from the fluid to the solid particles and hence the pressure drop through the bed is related to the physical mechanism by which the flow occurs. The flow path through a bed of solid particles is composed of many differently shaped inter-connecting channels. Due to the nature of the channels and the fluid flow pattern, it is necessary to study the flow through a bed of solid particles as a macro-system, i.e. the total cross-sectional area of the bed. Fanning used the following equation for the flow of liquid in pipes:

$$\Delta p = \frac{2 f L \rho_f u_f^2}{g d} \tag{6.1}$$

where '$f$ ' is the friction factor and $u$ is liquid velocity. The friction factor $f$ is a function of Reynolds number and bed voidage. Many investigators have sought to derive emperical correlation for the friction factor ($f$). However, the variables like the particle shape, roughness, distribution, manner of packing and similar difficultly definable parameters have made the task quite complicated. There are at present several well recognised correlations which permit reasonably accurate prediction of pressure drop through a bed of spherical or non-spherical material. These are of Blake [6], Carman [7], Chilton-Colburn [8], Oman and Watson, Leva and Coworkers, Happel, Ergun, Rose and Rizk mentioned in 'Fluidization and Fluid-particle system' [2].

Particulate fluidization generally gives rise to a homogeneous fluidization. Actually, this ideal situation described is not realized exactly in practice and important deviations have been observed. Couderc and Angelino [3] have demonstrated experimentally that channelling results in differences in the local pressure drop through the fluidized bed, particularly near minimum fluidization.

For conditions a little below or above minimum fluidization, the tendency of channel formation depends on stability conditions. In order to ensure stable operation with uniform fluidization, it is apparent that the pressure drop through the distributor should be sufficiently large so that the flow rate through it is relatively undisturbed by the bed pressure fluctuation above it. If the net result is that the pressure drop across the combined bed and distributor increases with an increase in local velocity, then the channel formation will tend to be damped out. The ratio of distributor to bed pressure drop at minimum fluidization velocity has usually been used as the criterion for multiorifice distributor design. Hiby [9] indicated that for a porous distributor plate and condition near minimum fluidization, the pressure drop through the distributor should be atleast 30% of that through the bed to provide uniform fluidization. The required ratio of distributor-to-bed pressure drop increase moderately with particle size. Agarwal [10] recommended the distributor pressure drop to be 10% of the bed pressure drop when the bed is deep or of high density material. For shallow bed of low density material, it is recommended that the pressure drop through the distributor should not fall below 3.45 $kN/m^2$. Siegel [11] suggested that for a wide range of Galileo number ($1\text{-}10^4$), the minimum ratio of distributor to bed resistance required for the stability of a fluidized bed is between 0.14 and 0.22. Saxena et al [12] obtained this value to be 0.21. Experimental investigation of Whitehead and Dent [13] and theoretical analysis of Siegel [11] reported a pressure drop ratio as low as 0.05 and as high as 1.0. Sathiyamoorthy and Rao [14] obtained distributor to bed pressure drop ratio as 0.24 and 0.12 respectively for coarse and fine sized particles. Qureshi and Creasy [15] reported in their review that a number of investigators [10, 16-21] have obtained pressure drop ratios between 0.11 and 1.0 using multiorifice distributor plates.

In the present work an extensive study has been made to study the pressure drop ratio in gas-solid unpromoted fluidized beds as well as beds promoted with co-axial rod, disk and blade promoters. The bed pressure drop equations for the promoted beds have been formulated in the line of Ergun [22] and Burke-Plummer [23] using experimental data. The predicted values obtained with these equations have been compared with the experimental ones and those obtained from developed correlations based on dimensional analysis approach. A pressure drop equation for traditional gas-solid fluidized bed as given below (Eq. 6.2) has also been used to check and compare the results predicted.

$$\frac{\Delta p_b}{L} = \rho_s \left(1 - \varepsilon\right) g \tag{6.2}$$

The scope of the present investigation is given in Table-3.1.

## 6.2 Analysis of the data

The experimental data have been analyzed for the development of-

(i) correlations for distributor-to-bed pressure drop ratio

(ii) neural network-models for distributor-to-bed pressure drop ratio

(iii) bed pressure drop equation for the promoted bed in the line of Ergun and Burke Plummer

### 6.2.1 Development of correlations for distributor-to-bed pressure drop ratio (Dimensional analysis method)

Distributor-to-bed pressure drop ratio $(\Delta p_d / \Delta p_b)$ can be expressed as functions of dimensionless groups containing bed, distributor and promoter parameters and the properties of the fluidized particles and the medium as:

$$\frac{\Delta p_d}{\Delta p_b} = K\left[\left(G_{mrf}\right)^a \left(\frac{\rho_s}{\rho_f}\right)^b \left(\frac{A_{do}}{A_c}\right)^c \left(\frac{d_p}{d_o}\right)^d \left(\frac{h_s}{D_c}\right)^e \left(\frac{D_e}{D_c}\right)^f \left(\frac{t}{D_c}\right)^g \left(\frac{D_k}{D_c}\right)^h\right]^n \qquad (6.3)$$

Analyzing the experimental data for the effect of individual dimensionless parameter, the values of the constants and the exponents have been obtained by the regression analysis of the data for respective beds. Using the correlation plots (Figs. 6.1 to 6.4), the final expressions for pressure drop ratio respectively for unpromoted and promoted beds with rod, disk and blade promoters have been obtained as under:

**Unpromoted bed**

$$\frac{\Delta p_d}{\Delta p_b} = 1.29\times10^{-4}\left(G_{mrf}\right)^{1.14}\left(\frac{\rho_s}{\rho_f}\right)^{0.48}\left(\frac{A_{do}}{A_c}\right)^{-1.83}\left(\frac{d_p}{d_o}\right)^{0.89}\left(\frac{h_s}{D_c}\right)^{-1.02} \qquad (6.4)$$

**Bed with rod promoter**

$$\frac{\Delta p_d}{\Delta p_b} = 8.66\times10^{-5}\left(G_{mrf}\right)^{1.26}\left(\frac{\rho_s}{\rho_f}\right)^{0.53}\left(\frac{A_{do}}{A_c}\right)^{-2.01}\left(\frac{d_p}{d_o}\right)^{0.94}$$

$$\mathrm{X}\left(\frac{h_s}{D_c}\right)^{-1.18}\left(\frac{D_e}{D_c}\right)^{-0.21} \qquad (6.5)$$

**Bed with disk promoter**

$$\frac{\Delta p_d}{\Delta p_b} = 9.41\times10^{-5}\left(G_{mrf}\right)^{1.16}\left(\frac{\rho_s}{\rho_f}\right)^{0.51}\left(\frac{A_{do}}{A_c}\right)^{-1.9}\left(\frac{d_p}{d_o}\right)^{0.93}\left(\frac{h_s}{D_c}\right)^{-1.06}$$

$$\mathrm{X}\left(\frac{t}{D_c}\right)^{-0.12}\left(\frac{D_k}{D_c}\right)^{0.22} \qquad (6.6)$$

**Bed with blade promoter**

$$\frac{\Delta p_d}{\Delta p_b} = 1.31\times10^{-4}\left(G_{mrf}\right)^{1.17}\left(\frac{\rho_s}{\rho_f}\right)^{0.48}\left(\frac{A_{do}}{A_c}\right)^{-1.87}\left(\frac{d_p}{d_o}\right)^{0.92}\left(\frac{h_s}{D_c}\right)^{-1.04} \qquad (6.7)$$

### 6.2.2 Development and use of artificial neural network models for distribuor-to-bed pressure drop ratio

Artificial neural network (ANN) models to predict distribuor-to-bed pressure drop ratio $(\Delta p_d / \Delta p_b)$ for unpromoted bed and beds promoted with rod, disk and blade promoters have been developed on similar lines as explained in article 4.2.1. Tables 6.1-6.4 present sum-squared error for various ANN structures (I X H X O) and Table 6.5 indicates the ANN structures selected (based on least error criterion) for different beds. The comparison between the predicted values of distribuor-to-bed pressure drop ratio using ANN-models and the corresponding experimental values (Tables 6.6 to 6.9) show that all the four ANN-models for different beds have been trained to a satisfactory level. Further, the values of the co-efficient of determination ( $R^2$ ) for training and testing data in case of unpromoted bed and beds promoted with rod, disk and blade promoters obtained respectively as (0.99,0.9858), (0.9966,0.9674), (0.9933,0.9883) and (0.9933,0.9785), support the above claim.

### 6.2.3 Formulation of Bed pressure drop equation for promoted bed in the line of Ergun and Burke-Plummer

The pressure drop through packed beds of uniformly granular material was correlated by Ergun [22] is given as:

$$\frac{\Delta p_b}{L} = \frac{150(1-\varepsilon)^2 \mu_f u_f}{\varepsilon^3 (\phi_s d_p)^2} + \frac{1.75(1-\varepsilon)\rho_f u_f^2}{\varepsilon^3 \phi_s d_p} \tag{6.8}$$

The above Eq. 6.8 in general can be written as:

$$\frac{\Delta p_b}{L} = \mathrm{K}_1 \frac{(1-\varepsilon)^2 \mu_f u_f}{\varepsilon^3 \phi_s^2 d_p^2} + \mathrm{K}_2 \frac{(1-\varepsilon)}{\varepsilon^3} \frac{\rho_f u_f^2}{\phi_s d_p} \tag{6.9}$$

or, $$\frac{\Delta p_b}{L} \frac{\varepsilon^3 \phi_s^2 d_p^2}{(1-\varepsilon)^2 \mu_f u_f} = \mathrm{K}_1 + \mathrm{K}_2 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_f u_f^2}{\phi_s d_p} \frac{\varepsilon^3 \phi_s^2 d_p^2}{(1-\varepsilon)^2 \mu_f u_f}$$

At higher Reynolds number, constant $\mathrm{K}_1$ is neglected (Burke-Plummer equation)

i.e. $$\frac{\Delta p_b}{L} \frac{\varepsilon^3 \phi_s^2 d_p^2}{(1-\varepsilon)^2 \mu_f u_f} = \mathrm{K}_2 \frac{1-\varepsilon}{\varepsilon^3} \frac{\rho_f u_f^2}{\phi_s d_p} \frac{\varepsilon^3 \phi_s^2 d_p^2}{(1-\varepsilon)^2 \mu_f u_f}$$

$$= \mathrm{K}_2 \frac{\rho_f u_f \phi_s d_p}{(1-\varepsilon)\mu_f} = \mathrm{K}_2 N_{\mathrm{Re}}' = f_v \tag{6.10}$$

In the present case-

$\varepsilon = \dfrac{V_e - V_s - V_p}{V_e}$, And $L = R.h_s$

For unpromoted bed, Singh [24] reported the value of $\mathrm{K}_2$ to be independent of particle size and density and initial static bed height. However, for the promoted beds the constant $\mathrm{K}_2$ will depend on the type of promoters used in the beds and can be obtained as the slopes of the respective plots between $f_v$ versus modified Reynolds number on Cartesian coordinates for beds with rod, disk and blade promoters. The values of $\mathrm{K}_2$ as obtained from the experimental plots of $f_v$ versus modified Reynolds number for the beds with rod, disk and blade promoters (Figs. 6.5 to 6.7) have been presented in Table 6.10 Thus, the pressure drop for fluidized beds can be obtained from Eq. 6.10 as-

$$\text{or, } \Delta p_b = K_2 L N_{\mathrm{Re}}{}' \frac{(1-\varepsilon)^2 \mu_f u_f}{\varepsilon^3 \phi_s^2 d_p^2} \tag{6.11}$$

## **6.3** Results and discussion

The comparative variation of distributor-to-bed pressure drop ratio ($\Delta p_d / \Delta p_b$) with non-dimensional system parameter for different beds have been shown in Figs. 6.8 to 6.12 and with rod and disk promoter parameters in Figs. 6.13 to 6.15 under identical operating conditions. The values of pressure drop ratio predicted with the help of developed correlations: Eqs. 6.4 to 6.7 respectively for unpromoted bed and beds with rod, disk and blade type of promoters have been compared with the corresponding experimental ones and those predicted from ANN-models (Tables 6.6 to 6.9 for randomized data). From the comparison Tables 6.6-6.9, the predicted results using developed correlations have been found to be in good agreement with the corresponding experimental values and those obtained by ANN-models. The mean and standard deviations of the experimental values from the calculated ones (using the above two methods) for pressure drop ratio in case of unpromoted and promoted beds with rod, disk and blade promoters have been given in Table 6.11.

Further, it can be observed that the developed correlations using dimensional analysis approach as well as ANN-models can be satisfactorily used for the prediction of pressure drop ratio in the respective beds. From the Table 6.11, it has been found that the values predicted by the ANN-models are better with reduced standard and mean deviation.

A Comparison between the predicted values of bed pressure drop using (i) developed correlations (Eqs. 6.4 to 6.7), (ii) modified Burke-Plummer equation (Eq. 6.11) and (iii) Eq. 6.2 for traditional bed, with the corresponding experimental ones have been shown in Figs. 6.16 to 6.18 for respective beds. One such comparison for beds with equal volume blockage of rod, disk and blade promoters has been presented in Table 6.12. The mean of the absolute values of percentage deviation of the predicted values of bed pressure drop from the respective experimental ones and the corresponding standard deviation have been presented in Table 6.13. Although the mean and standard deviation of the predicted bed pressure drop using traditional equation for most of the promoted beds have been found to be close to that obtained by modified Burke-Plummer equation, it can be observed (Table 6.12) that the traditional equation gives higher values of bed pressure drop at low modified Reynolds number and vice versa in comparison to the experimental ones. Thus, the predicted values of bed pressure drop using developed correlations and modified Burke-Plummer equation show uniform and close agreement with the experimental data throughout the range of modified Reynolds number.

## 6.4 Conclusion

From the developed correlations and the comparison of the results, distributor-to-bed pressure drop ratio has been found to be influenced by the system variables. It can be concluded that:

(i) The distributor-to-bed pressure drop ratio increases with mass velocity.

(ii) The $\Delta p_d / \Delta p_b$ values increases with decrease in open area showing minimum channelling and improved gas-solid fluidization. For most of the distributors, the pressure drop ratio lie within the recommended range excepting for the distributor having open area ratio of 1.43% for which this ratio is higher. The higher pressure drop ratio for the same distributor with different operating parameters means low bed pressure drop, hence low power cost. On the other hand, a higher pressure drop ratio with decreasing distributor open area results in high power cost with identical operating parameters. But the distributors of low open area ratio have been found to perform better in fluidization. The distributor having open area ratio of 12.9% show a little lower value of $\Delta p_d / \Delta p_b$.

(iii) It can also be concluded that the interference of promoters increases the distributor- to -bed pressure drop ratio i.e. the bed pressure drop is reduced which may lead to channelling. However, the distributors of low open area ratio perform better in reducing bed expansion and fluctuation and thereby reduce the height of equipment and thus the manufacturing cost.

(iv) It has also been observed that the use of disk and blade promoters show marginal increase in $\Delta p_d / \Delta p_b$ values whereas the rod promoters significantly increase this ratio. In beds promoted with rod promoters, $\Delta p_d / \Delta p_b$ increases with decrease in equivalent diameter $(D_e)$ i.e. increases with number of vertical rods which may be attributed to the loose packing of the material around the periphery of the rods. In beds with disk promoters, $\Delta p_d / \Delta p_b$ values have been found to decrease with increase in disk thickness and decrease in disk diameter of the disk promoters. The increase in disk thickness and decrease in disk diameter cause reduction in entrapped material which results in decrease of pressure drop ratio i.e. increase in bed pressure drop because of enhanced secondary flow.

(v) Also, $\Delta p_d / \Delta p_b$ increases rapidly with increase in particle size i.e. increase in fluidization velocity which agrees with the findings of Saxena et al. [12].

With respect to the comparison plots between the experimental and the calculated values of bed pressure drop (Figs. 6.16 to 6.18), it is obvious that the developed correlations and Eq. 6.11 can be used for the prediction of bed pressure drop in the range of the experiment. The calculated values of bed pressure drop using modified Burke-Plummer equation have been found to have larger mean and standard deviations (Table 6.13) when compared with the values obtained by the developed correlations (Eqs. 6.5 to 6.7) for respective beds. In other words, the prediction of bed pressure drop with the help of Eqs. 6.5 to 6.7 are more close to the experimental values than those obtained from modified Burke-Plummer equation (Tables 6.12 and 6.13). This may be due to a single value of the constant $K_2$ used for a bed with particular type of promoter and neglecting the effects of other bed and distributor parameters. It has also been observed that the modified Burke-Plummer equations are applicable for promoted gas-solid fluidized beds using mostly Geldart [25, 26] "D" type particle or particle close to this type. Further, it can be concluded that the modified Burke-Plummer equations are more suitable, simple and generalized and can be used for beds with different promoters of varying system parameters.

# Nomenclature

| | |
|---|---|
| $A_c$ | cross sectional area of column, $L^2$ |
| $A_{do}$ | open area of distributor, $L^2$ |
| $A_o$ | open area in promoted bed with rod promoters, $L^2$ |
| BP | bed with blade type of promoter |
| $D_c$ | column diameter, L |
| $D_e$ | equivalent diameter of promoted bed, $4A_0/P$ ,  L |
| $D_k$ | disk diameter, L |
| DP | bed with disk promoter |
| d | pipe diameter, L |
| $d_o$ | orifice diameter, L |
| $d_p$ | particle size, L |
| $Ga$ | Galelio number, $d_p^3 \rho_f^2 g / \mu_f^2$ |
| $G_f$ | fluidization mass velocity, $ML^{-2}T^{-1}$ |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted beds, $ML^{-2}T^{-1}$ |
| $G_{mf}^{'}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $G_{mrf}$ | reduced fluidization mass velocity in unpromoted beds, $G_f / G_{mf}$ |
| | reduced fluidization mass velocity in promoted beds, $G_f / G_{mf}$ |
| $L$ | expanded bed height, $(h_{\max} + h_{\min})/2$, L |
| $h_{\max}$ | maximum height of fluidized bed, L |
| $h_{\min}$ | minimum  height of fluidized bed, L |
| $h_s$ | initial static bed height, L |
| $L$ | expanded bed height, $R.h_s$ ,  L |
| $N_{\mathrm{Re}}^{'}$ | modified Reynolds number, $(\rho_f u \phi d_p)/(1-\varepsilon)\mu_f$ |

| | |
|---|---|
| $P$ | total rod perimeter, L |
| $R$ | bed expansion ratio, $L/h_s$ |
| RP | bed with rod promoter |
| $t$ | disk thickness, L |
| $u_f$ | superficial fluid velocity, $LT^{-1}$ |
| UP | unpromoted bed |
| $V_e$ | volume of the expanded bed, $L^3$ |
| $V_p$ | volume of promoter, $L^3$ |
| $V_s$ | volume of solid, $L^3$ |

***Greek Letters***

| | |
|---|---|
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |
| $\varepsilon$ | porosity |
| $\phi_s$ | sphericity |
| $\Delta p_b$ | bed pressure drop, $ML^{-1}T^{-2}$ |
| $\Delta p_d$ | distributor pressure drop, $ML^{-1}T^{-2}$ |
| $\mu_f$ | viscosity, $ML^{-1}T^{-1}$ |

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**Table 6.1** Sum squared error (SSE) for various ANN structure tested for unpromoted bed

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H x O ) | Sum squared error |
| 5 2 1 | 0.188072 |
| 5 4 1 | 0.188359 |
| 5 6 1 | 0.187198 |
| 5 8 1 | 0.185574 |
| 5 10 1 | 0.186427 |
| 5 13 1 | 0.186645 |
| 5 14 1 | 0.187846 |
| 5 16 1 | 0.186864 |
| 5 18 1 | 0.185528 |
| 5 19 1 | 0.185919 |
| 5 20 1* | 0.185263 |
| 5 21 1 | 0.187413 |
| 5 23 1 | 0.18685 |

* selected structure

**Table 6.2** Sum squared error (SSE) for various ANN structure tested for bed with rod promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H x O ) | Sum squared error |
| 6 2 1 | 0.135667 |
| 6 4 1 | 0.135093 |
| 6 7 1 | 0.136253 |
| 6 9 1 | 0.133816 |
| 6 10 1 | 0.135843 |
| 6 12 1 | 0.136467 |
| 6 13 1 | 0.133876 |
| 6 14 1 | 0.135012 |
| 6 16 1 | 0.134626 |
| 6 17 1 | 0.134012 |
| 6 18 1 | 0.133925 |
| 6 19 1 | 0.133505 |
| 6 20 1* | 0.13296 |
| 6 21 1 | 0.134073 |
| 6 22 1 | 0.182727 |

* selected structure

**Table 6.3** Sum squared error (SSE) for various ANN structure tested for bed with disk promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H x O ) | Sum squared error |
| 7 2 1 | 0.142758 |
| 7 4 1 | 0.142845 |
| 7 6 1 | 0.142541 |
| 7 8 1 | 0.143347 |
| 7 9 1 | 0.141714 |
| 7 11 1 | 0.14041 |
| 7 12 1 | 0.141513 |
| 7 14 1 | 0.139225 |
| 7 16 1 | 0.140415 |
| 7 17 1* | 0.138707 |
| 7 18 1 | 0.141045 |
| 7 19 1 | 0.1408 |
| 7 20 1 | 0.139027 |
| 7 21 1 | 0.139193 |
| 7 22 1 | 0.140889 |

* selected structure

**Table 6.4** Sum squared error (SSE) for various ANN structure tested for bed with blade promoter

| Constants: learning rate=0.001, no. of cycles=1000 | |
|---|---|
| ANN structures ( I x H X O ) | Sum squared error |
| 5 2 1 | 0.166816 |
| 5 4 1 | 0.16706 |
| 5 5 1 | 0.165612 |
| 5 6 1 | 0.166161 |
| 5 7 1 | 0.16461 |
| 5 9 1 | 0.166164 |
| 5 10 1 | 0.16447 |
| 5 12 1 | 0.164077 |
| 5 14 1 | 0.164384 |
| 5 15 1 | 0.164005 |
| 5 16 1* | 0.162071 |
| 5 17 1 | 0.163265 |
| 5 18 1 | 0.163256 |
| 5 19 1 | 0.163124 |
| 5 20 1 | 0.164655 |

* selected structure

**Table 6.5** Selected structures of neural network models for test problems undertaken

| Learning rate 0.001-0.100 | | | | |
|---|---|---|---|---|
| Bed particulars | Input Nodes | Hidden Nodes | Output Nodes | Number of cycles used for Training |
| Unpromoted bed | 5 | 20 | 1 | 50,000 |
| Bed with rod promoter | 6 | 20 | 1 | 50,000 |
| Bed with disk promoter | 7 | 17 | 1 | 50,000 |
| Bed with blade promoter | 5 | 16 | 1 | 50,000 |

**Table 6.6** Comparison between experimental and calculated (Eq. 6.4 and ANN-models) values of distributor-to-bed pressure drop ratio for unpromoted bed

| Serial No. | System variables | | | | | Pressure drop ratio $(\Delta p_d / \Delta p_b)$ | | |
|---|---|---|---|---|---|---|---|---|
| | $G_{mrf}$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | Exptl. | Predicted by | |
| | | | | | | | Eq. 6.4 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 1.410 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.092 | 0.090 | 0.097 |
| 2 | 1.527 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.097 | 0.098 | 0.104 |
| 3 | 1.644 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.103 | 0.112 | 0.107 |
| 4 | 1.762 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.112 | 0.119 | 0.116 |
| 5 | 2.380 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.172 | 0.163 | 0.164 |
| 6 | 1.625 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.086 | 0.083 | 0.082 |
| 7 | 1.857 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.085 | 0.094 | 0.096 |
| 8 | 3.25 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.153 | 0.182 | 0.152 |
| 9 | 1.043 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.081 | 0.090 | 0.074 |
| 10 | 1.148 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.087 | 0.083 | 0.095 |
| 11 | 1.252 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.094 | 0.092 | 0.101 |
| 12 | 1.356 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.098 | 0.100 | 0.107 |
| 13 | 1.461 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.103 | 0.113 | 0.109 |
| 14 | 1.774 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.129 | 0.136 | 0.136 |
| 15 | 1.878 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.138 | 0.146 | 0.145 |
| 16 | 2.501 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.197 | 0.202 | 0.208 |
| 17 | 1.062 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.097 | 0.085 | 0.102 |
| 18 | 1.138 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.104 | 0.092 | 0.106 |
| 19 | 1.214 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.108 | 0.099 | 0.110 |
| 20 | 1.365 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.116 | 0.120 | 0.113 |
| 21 | 1.441 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.121 | 0.125 | 0.120 |
| 22 | 1.537 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.132 | 0.129 |
| 23 | 1.175 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.138 | 0.151 | 0.168 |
| 24 | 1.292 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.152 | 0.188 | 0.165 |
| 25 | 1.410 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.170 | 0.207 | 0.182 |
| 26 | 1.644 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.208 | 0.222 | 0.247 |
| 27 | 1.762 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.255 | 0.267 | 0.247 |
| 28 | 2.114 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.378 | 0.329 | 0.345 |

Continued on next page

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 29 | 2.380 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.45 | 0.376 | 0.449 |
| 30 | 1.175 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.395 | 0.484 | 0.382 |
| 31 | 1.292 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.44 | 0.443 | 0.540 |
| 32 | 1.410 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.490 | 0.596 | 0.512 |
| 33 | 1.568 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.063 | 0.068 | 0.065 |
| 34 | 1.792 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.069 | 0.074 | 0.079 |
| 35 | 2.016 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.084 | 0.091 | 0.084 |
| 36 | 3.136 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.124 | 0.129 | 0.150 |
| 37 | 3.584 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.141 | 0.174 | 0.141 |
| 38 | 1.155 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.047 | 0.041 | 0.045 |
| 39 | 1.270 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.051 | 0.046 | 0.048 |
| 40 | 1.444 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.055 | 0.053 | 0.053 |
| 41 | 2.31 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.079 | 0.091 | 0.084 |
| 42 | 2.887 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.101 | 0.117 | 0.104 |
| 43 | 3.464 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.117 | 0.144 | 0.117 |
| 44 | 4.041 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.141 | 0.172 | 0.126 |
| 45 | 1.140 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.042 | 0.035 | 0.040 |
| 46 | 1.520 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.052 | 0.048 | 0.049 |
| 47 | 1.901 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.058 | 0.062 | 0.061 |
| 48 | 2.281 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.067 | 0.077 | 0.073 |
| 49 | 3.041 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.09 | 0.106 | 0.095 |
| 50 | 1.057 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.115 | 0.126 | 0.097 |
| 51 | 1.175 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.128 | 0.110 | 0.135 |
| 52 | 1.292 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.136 | 0.144 | 0.122 |
| 53 | 1.410 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.153 | 0.135 | 0.154 |
| 54 | 1.527 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.157 | 0.148 | 0.165 |
| 55 | 2.114 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.230 | 0.215 | 0.230 |
| 56 | 2.349 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.260 | 0.242 | 0.268 |
| 57 | 1.175 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.058 | 0.054 | 0.060 |
| 58 | 1.292 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.061 | 0.061 | 0.064 |
| 59 | 1.410 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.069 | 0.068 | 0.067 |
| 60 | 2.815 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.140 | 0.147 | 0.151 |
| 61 | 1.057 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.045 | 0.038 | 0.048 |
| 62 | 1.175 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.050 | 0.051 | 0.043 |
| 63 | 1.410 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.055 | 0.053 | 0.056 |
| 64 | 1.880 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.067 | 0.074 | 0.070 |
| 65 | 2.349 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.089 | 0.095 | 0.089 |

**Table 6.7** Comparison between experimental and calculated (Eq. 6.5 and ANN-models) values of distributor-to-bed pressure drop ratio for bed with rod promoter

| Serial No. | System variables | | | | | | Pressure drop ratio $(\Delta p_d / \Delta p_b)$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $G_{mrf}$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | $D_e / D_c$ | Exptl. | Predicted by | |
| | | | | | | | | Eq. 6.5 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 1 | 1.484 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 0.116 | 0.119 | 0.117 |
| 2 | 1.696 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 0.143 | 0.141 | 0.138 |
| 3 | 1.908 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 0.163 | 0.164 | 0.160 |
| 4 | 2.345 | 2347.5 | 0.09 | 0.29 | 2.36 | 1.248 | 0.22 | 0.212 | 0.208 |
| 5 | 1.519 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 0.106 | 0.111 | 0.109 |
| 6 | 1.845 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 0.140 | 0.139 | 0.141 |
| 7 | 1.953 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 0.149 | 0.149 | 0.152 |
| 8 | 2.601 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 0.22 | 0.227 | 0.214 |
| 9 | 2.170 | 2347.5 | 0.09 | 0.29 | 2.36 | 2.209 | 0.171 | 0.171 | 0.175 |
| 10 | 1.767 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 0.161 | 0.161 | 0.162 |
| 11 | 1.871 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 0.173 | 0.173 | 0.174 |
| 12 | 1.975 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 0.188 | 0.185 | 0.187 |
| 13 | 2.107 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 0.210 | 0.204 | 0.201 |
| 14 | 2.299 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.856 | 0.232 | 0.228 | 0.224 |
| 15 | 1.227 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 0.111 | 0.108 | 0.109 |
| 16 | 1.431 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 0.130 | 0.131 | 0.132 |
| 17 | 1.636 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 0.150 | 0.155 | 0.157 |
| 18 | 2.072 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 0.220 | 0.209 | 0.216 |
| 19 | 2.261 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.642 | 0.238 | 0.233 | 0.243 |
| 20 | 1.677 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 0.094 | 0.106 | 0.107 |
| 21 | 1.886 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 0.109 | 0.123 | 0.122 |
| 22 | 2.934 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 0.176 | 0.215 | 0.193 |
| 23 | 4.191 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 0.285 | 0.337 | 0.301 |
| 24 | 2.096 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 0.120 | 0.141 | 0.136 |
| 25 | 3.772 | 1409.2 | 0.09 | 0.29 | 2.36 | 1.248 | 0.277 | 0.295 | 0.255 |
| 26 | 1.130 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 0.098 | 0.100 | 0.097 |
| 27 | 1.412 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 0.123 | 0.133 | 0.128 |
| 28 | 2.256 | 3245.8 | 0.09 | 0.29 | 2.36 | 1.248 | 0.240 | 0.240 | 0.250 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|
| 29 | 1.026 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 0.104 | 0.100 | 0.093 |
| 30 | 1.095 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 0.112 | 0.109 | 0.100 |
| 31 | 1.231 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 0.128 | 0.126 | 0.116 |
| 32 | 1.368 | 4066.7 | 0.09 | 0.29 | 2.36 | 1.248 | 0.139 | 0.144 | 0.135 |
| 33 | 1.696 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 0.318 | 0.353 | 0.339 |
| 34 | 2.120 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 0.465 | 0.501 | 0.468 |
| 35 | 2.148 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 0.510 | 0.512 | 0.476 |
| 36 | 1.908 | 2347.5 | 0.057 | 0.29 | 2.36 | 1.248 | 0.395 | 0.410 | 0.418 |
| 37 | 1.060 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 0.520 | 0.624 | 0.767 |
| 38 | 1.166 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 0.580 | 0.703 | 0.812 |
| 39 | 1.272 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 0.660 | 0.785 | 0.851 |
| 40 | 1.484 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 0.800 | 0.953 | 0.908 |
| 41 | 1.696 | 2347.5 | 0.032 | 0.29 | 2.36 | 1.248 | 0.945 | 0.945 | 1.128 |
| 42 | 1.821 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 0.102 | 0.101 | 0.103 |
| 43 | 2.225 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 0.115 | 0.130 | 0.122 |
| 44 | 2.427 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 0.119 | 0.145 | 0.132 |
| 45 | 2.630 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 0.137 | 0.161 | 0.141 |
| 46 | 3.641 | 2347.5 | 0.09 | 0.185 | 2.36 | 1.248 | 0.198 | 0.202 | 0.242 |
| 47 | 1.561 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 0.082 | 0.071 | 0.080 |
| 48 | 1.822 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 0.089 | 0.086 | 0.090 |
| 49 | 2.082 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 0.099 | 0.102 | 0.100 |
| 50 | 2.602 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 0.111 | 0.119 | 0.135 |
| 51 | 3.123 | 2347.5 | 0.09 | 0.156 | 2.36 | 1.248 | 0.141 | 0.141 | 0.17 |
| 52 | 2.741 | 2347.5 | 0.09 | 0.131 | 2.36 | 1.248 | 0.100 | 0.122 | 0.107 |
| 53 | 1.060 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 0.124 | 0.125 | 0.135 |
| 54 | 1.166 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 0.142 | 0.141 | 0.150 |
| 55 | 2.345 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 0.37 | 0.359 | 0.341 |
| 56 | 2.541 | 2347.5 | 0.09 | 0.29 | 1.58 | 1.248 | 0.420 | 0.377 | 0.398 |
| 57 | 1.060 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 0.061 | 0.056 | 0.057 |
| 58 | 1.166 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 0.066 | 0.063 | 0.063 |
| 59 | 2.148 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 0.143 | 0.135 | 0.133 |
| 60 | 2.541 | 2347.5 | 0.09 | 0.29 | 3.15 | 1.248 | 0.167 | 0.167 | 0.164 |
| 61 | 1.060 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 0.045 | 0.043 | 0.044 |
| 62 | 1.696 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 0.072 | 0.077 | 0.077 |
| 63 | 2.120 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 0.105 | 0.102 | 0.105 |
| 64 | 2.148 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 0.109 | 0.104 | 0.107 |
| 65 | 2.541 | 2347.5 | 0.09 | 0.29 | 3.94 | 1.248 | 0.128 | 0.128 | 0.134 |

**Table 6.8** Comparison between experimental and calculated (Eq. 6.6 and ANN-models) values of distributor-to-bed pressure drop ratio for bed with disk promoter

| Serial No. | System variables | | | | | | | Pressure drop ratio ($\Delta p_d / \Delta p_b$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $G_{mrf}$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | $t / D_c$ | $D_k / D_c$ | Exptl. | Predicted by | |
| | | | | | | | | | Eq. 6.6 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
| 1 | 1.362 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.098 | 0.098 | 0.099 |
| 2 | 1.589 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.110 | 0.117 | 0.116 |
| 3 | 1.197 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 0.091 | 0.092 | 0.095 |
| 4 | 2.205 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 0.190 | 0.186 | 0.187 |
| 5 | 2.406 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 0.216 | 0.206 | 0.209 |
| 6 | 2.608 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.063 | 0.551 | 0.230 | 0.226 | 0.231 |
| 7 | 1.150 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 0.083 | 0.077 | 0.081 |
| 8 | 2.185 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 0.168 | 0.161 | 0.163 |
| 9 | 2.300 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 0.178 | 0.171 | 0.174 |
| 10 | 2.331 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.188 | 0.551 | 0.191 | 0.174 | 0.177 |
| 11 | 1.852 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 0.126 | 0.129 | 0.132 |
| 12 | 1.968 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 0.135 | 0.133 | 0.143 |
| 13 | 2.083 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 0.143 | 0.148 | 0.154 |
| 14 | 1.620 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.250 | 0.551 | 0.104 | 0.110 | 0.113 |
| 15 | 1.164 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 0.081 | 0.076 | 0.085 |
| 16 | 1.27 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 0.088 | 0.084 | 0.092 |
| 17 | 1.905 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 0.135 | 0.135 | 0.142 |
| 18 | 2.011 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 0.147 | 0.143 | 0.152 |
| 19 | 2.117 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.398 | 0.155 | 0.152 | 0.162 |
| 20 | 1.848 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 0.144 | 0.146 | 0.146 |
| 21 | 1.963 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 0.152 | 0.156 | 0.158 |
| 22 | 2.079 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.669 | 0.160 | 0.167 | 0.170 |
| 23 | 1.395 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.770 | 0.110 | 0.109 | 0.113 |
| 24 | 1.628 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.770 | 0.127 | 0.130 | 0.135 |
| 25 | 1.861 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.125 | 0.770 | 0.149 | 0.152 | 0.159 |
| 26 | 1.347 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.079 | 0.075 | 0.070 |
| 27 | 1.572 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.091 | 0.089 | 0.081 |
| 28 | 3.593 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.210 | 0.233 | 0.199 |

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| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 29 | 3.817 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.227 | 0.25 | 0.212 |
| 30 | 4.042 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.238 | 0.267 | 0.225 |
| 31 | 1.109 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.092 | 0.091 | 0.094 |
| 32 | 1.513 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.124 | 0.131 | 0.128 |
| 33 | 1.613 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.136 | 0.141 | 0.137 |
| 34 | 1.815 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.155 | 0.161 | 0.158 |
| 35 | 2.603 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.24 | 0.245 | 0.256 |
| 36 | 1.319 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.125 | 0.125 | 0.122 |
| 37 | 1.465 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.136 | 0.141 | 0.137 |
| 38 | 1.485 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.142 | 0.143 | 0.139 |
| 39 | 1.62 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.158 | 0.159 | 0.153 |
| 40 | 1.756 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.125 | 0.551 | 0.165 | 0.174 | 0.169 |
| 41 | 1.135 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 0.164 | 0.189 | 0.165 |
| 42 | 1.589 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 0.240 | 0.279 | 0.279 |
| 43 | 1.816 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 0.320 | 0.326 | 0.354 |
| 44 | 2.043 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.125 | 0.551 | 0.380 | 0.374 | 0.440 |
| 45 | 1.135 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 0.490 | 0.566 | 0.539 |
| 46 | 1.248 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 0.530 | 0.632 | 0.603 |
| 47 | 1.589 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 0.71 | 0.836 | 0.776 |
| 48 | 1.816 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.125 | 0.551 | 0.91 | 0.976 | 0.861 |
| 49 | 1.300 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 0.069 | 0.061 | 0.069 |
| 50 | 1.517 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 0.073 | 0.073 | 0.079 |
| 51 | 1.733 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 0.080 | 0.085 | 0.088 |
| 52 | 3.684 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.125 | 0.551 | 0.168 | 0.205 | 0.18 |
| 53 | 1.116 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 0.055 | 0.044 | 0.056 |
| 54 | 3.347 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.125 | 0.551 | 0.127 | 0.156 | 0.132 |
| 55 | 1.029 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 0.041 | 0.034 | 0.050 |
| 56 | 1.102 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 0.045 | 0.037 | 0.052 |
| 57 | 2.939 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 0.092 | 0.114 | 0.100 |
| 58 | 3.307 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 0.108 | 0.131 | 0.110 |
| 59 | 3.674 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.125 | 0.551 | 0.120 | 0.148 | 0.124 |
| 60 | 1.929 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 0.217 | 0.225 | 0.235 |
| 61 | 2.043 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.125 | 0.551 | 0.230 | 0.240 | 0.251 |
| 62 | 1.248 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 0.067 | 0.065 | 0.068 |
| 63 | 2.270 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 0.130 | 0.131 | 0.140 |
| 64 | 2.300 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.125 | 0.551 | 0.140 | 0.133 | 0.143 |
| 65 | 2.270 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.125 | 0.551 | 0.104 | 0.103 | 0.116 |

**Table 6.9** Comparison between experimental and calculated (Eq. 6.7 and ANN-model) values of distributor-to-bed pressure drop ratio for bed with blade promoter

| Serial No. | System variables | | | | | Pressure drop ratio ($\Delta p_d / \Delta p_b$) | | |
|---|---|---|---|---|---|---|---|---|
| | $G_{mrf}$ | $\rho_s / \rho_f$ | $A_{do} / A_c$ | $d_p / d_o$ | $h_s / D_c$ | Exptl. | Predicted by | |
| | | | | | | | Eq. 6.7 | ANN-model |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 1.715 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.115 | 0.120 | 0.120 |
| 2 | 1.929 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.131 | 0.139 | 0.135 |
| 3 | 2.143 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.153 | 0.157 | 0.149 |
| 4 | 2.172 | 2347.5 | 0.09 | 0.29 | 2.36 | 0.155 | 0.159 | 0.151 |
| 5 | 1.176 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.067 | 0.061 | 0.063 |
| 6 | 1.307 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.071 | 0.069 | 0.070 |
| 7 | 1.525 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.078 | 0.082 | 0.082 |
| 8 | 2.179 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.105 | 0.125 | 0.115 |
| 9 | 3.268 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.167 | 0.201 | 0.163 |
| 10 | 3.486 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.180 | 0.217 | 0.173 |
| 11 | 3.704 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.188 | 0.233 | 0.184 |
| 12 | 4.140 | 1409.2 | 0.09 | 0.29 | 2.36 | 0.220 | 0.265 | 0.213 |
| 13 | 1.234 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.103 | 0.096 | 0.100 |
| 14 | 1.519 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.119 | 0.123 | 0.123 |
| 15 | 1.709 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.135 | 0.141 | 0.138 |
| 16 | 1.899 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.149 | 0.159 | 0.154 |
| 17 | 2.275 | 3245.8 | 0.09 | 0.29 | 2.36 | 0.183 | 0.197 | 0.185 |
| 18 | 1.228 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.112 | 0.106 | 0.108 |
| 19 | 1.381 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.117 | 0.122 | 0.121 |
| 20 | 1.458 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.121 | 0.130 | 0.128 |
| 21 | 1.535 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.132 | 0.138 | 0.134 |
| 22 | 1.555 | 4066.7 | 0.09 | 0.29 | 2.36 | 0.135 | 0.140 | 0.136 |
| 23 | 1.072 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.143 | 0.164 | 0.142 |
| 24 | 1.715 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.280 | 0.284 | 0.286 |
| 25 | 1.822 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.313 | 0.305 | 0.315 |
| 26 | 1.929 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.340 | 0.326 | 0.344 |
| 27 | 2.036 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.380 | 0.347 | 0.375 |
| 28 | 2.172 | 2347.5 | 0.057 | 0.29 | 2.36 | 0.426 | 0.374 | 0.414 |

Continued on next page

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 29 | 1.072 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.390 | 0.482 | 0.431 |
| 30 | 1.179 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.440 | 0.539 | 0.490 |
| 31 | 1.286 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.480 | 0.597 | 0.548 |
| 32 | 1.393 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.530 | 0.656 | 0.605 |
| 33 | 1.500 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.575 | 0.715 | 0.658 |
| 34 | 1.715 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.726 | 0.836 | 0.752 |
| 35 | 1.929 | 2347.5 | 0.032 | 0.29 | 2.36 | 0.938 | 0.959 | 0.827 |
| 36 | 1.292 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.068 | 0.057 | 0.065 |
| 37 | 1.507 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.075 | 0.069 | 0.074 |
| 38 | 1.722 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.078 | 0.08 | 0.082 |
| 39 | 2.583 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.110 | 0.129 | 0.111 |
| 40 | 3.014 | 2347.5 | 0.09 | 0.185 | 2.36 | 0.124 | 0.155 | 0.124 |
| 41 | 1.231 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.061 | 0.046 | 0.056 |
| 42 | 1.338 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.064 | 0.051 | 0.06 |
| 43 | 1.499 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.067 | 0.058 | 0.066 |
| 44 | 1.873 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.075 | 0.076 | 0.077 |
| 45 | 3.211 | 2347.5 | 0.09 | 0.156 | 2.36 | 0.115 | 0.142 | 0.109 |
| 46 | 1.128 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.046 | 0.036 | 0.048 |
| 47 | 1.269 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.052 | 0.041 | 0.052 |
| 48 | 2.819 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.085 | 0.104 | 0.087 |
| 49 | 3.524 | 2347.5 | 0.09 | 0.131 | 2.36 | 0.110 | 0.135 | 0.100 |
| 50 | 1.072 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.124 | 0.106 | 0.115 |
| 51 | 1.715 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.181 | 0.183 | 0.194 |
| 52 | 1.822 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.212 | 0.197 | 0.208 |
| 53 | 1.929 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.220 | 0.211 | 0.222 |
| 54 | 2.143 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.240 | 0.238 | 0.251 |
| 55 | 2.568 | 2347.5 | 0.09 | 0.29 | 1.58 | 0.290 | 0.294 | 0.311 |
| 56 | 1.072 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.068 | 0.052 | 0.059 |
| 57 | 1.179 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.075 | 0.058 | 0.065 |
| 58 | 1.822 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.098 | 0.096 | 0.097 |
| 59 | 2.036 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.114 | 0.109 | 0.107 |
| 60 | 2.143 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.119 | 0.116 | 0.112 |
| 61 | 2.172 | 2347.5 | 0.09 | 0.29 | 3.15 | 0.122 | 0.118 | 0.113 |
| 62 | 1.715 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.073 | 0.071 | 0.080 |
| 63 | 1.822 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.079 | 0.076 | 0.085 |
| 64 | 2.036 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.088 | 0.087 | 0.092 |
| 65 | 2.143 | 2347.5 | 0.09 | 0.29 | 3.94 | 0.091 | 0.092 | 0.095 |

**Table 6.10** Experimental values of constant ($K_2$)

| Bed particulars | constant ($K_2$) |
|---|---|
| Bed with Rod promoter | 4.30 |
| Bed with Disk promoter | 4.65 |
| bed with Blade promoter | 5.05 |

**Table 6.11** Mean and standard deviations of predicted values of ($\Delta p_d / \Delta p_b$) from corresponding experimental ones

| Bed particulars | Standard deviation | | Mean | | No. of data |
|---|---|---|---|---|---|
| | Dimensional Analysis method | ANN-Model | Dimensional Analysis method | ANN-Model | |
| UP | 12.66 | 1.15 | 9.06 | 4.79 | 135 |
| RP | 10.10 | 7.13 | 7.05 | 4.43 | 157 |
| DP | 9.29 | 4.96 | 6.73 | 4.49 | 216 |
| BP | 12.84 | 5.50 | 10.13 | 4.49 | 135 |

**Table 6.12** Comparison between experimental and calculated values of bed pressure drop using Eqs. 6.5-6.7 and Modified Burke- Plummer equation (Eq. 6.11) for beds with rod, disk and blade promoter

| Bed particulars | Modified Reynolds no. $N'_{\mathrm{Re}}$ | Bed pressure drop (Pa) | | | |
|---|---|---|---|---|---|
| | | Eq. (6.11) | Experimental | Eqs. 6.5 to 6.7 for respective beds | Eq. 6.2 |
| Bed with rod promoter ($P_2$) | 64 | 1020 | 1340 | 1306 | 1769 |
| | 79 | 1198 | 1309 | 1325 | 1798 |
| | 94 | 1402 | 1340 | 1333 | 1825 |
| | 110 | 1631 | 1649 | 1667 | 1850 |
| | 113 | 1663 | 1908 | 1968 | 1853 |
| | 128 | 1897 | 2195 | 2277 | 1875 |
| | 145 | 2151 | 2607 | 2721 | 1897 |
| Bed with disk promoter ($P_6$) | 63 | 1106 | 1418 | 1329 | 1765 |
| | 77 | 1311 | 1418 | 1366 | 1790 |
| | 84 | 1423 | 1433 | 1379 | 1802 |
| | 92 | 1542 | 1433 | 1390 | 1813 |
| | 99 | 1666 | 1567 | 1585 | 1825 |
| | 107 | 1796 | 1760 | 1758 | 1836 |
| | 109 | 1832 | 2021 | 2077 | 1839 |
| | 124 | 2091 | 2300 | 2424 | 1858 |
| | 139 | 2370 | 2839 | 2921 | 1877 |
| Bed with blade promoter ($P_{12}$) | 60 | 1296 | 1558 | 1507 | 1749 |
| | 74 | 1531 | 1626 | 1547 | 1771 |
| | 87 | 1795 | 1665 | 1572 | 1791 |
| | 101 | 2086 | 2036 | 1986 | 1811 |
| | 103 | 2127 | 2412 | 2346 | 1813 |
| | 117 | 2422 | 2683 | 2736 | 1830 |
| | 131 | 2739 | 3275 | 3294 | 1846 |

**Table 6.13** Mean and standard deviation of predicted values of bed pressure drop from corresponding experimental ones

| Bed particulars | Modified Burke-Plummer equation (Eq. 6.11 ) | | Dimensional analysis approach ( Eqs. 6.5 to 6.7) | |
|---|---|---|---|---|
| | Mean | Standard deviation | Mean | Standard deviation |
| Bed with Rod promoter | 21.35 | 25.40 | 7.69 | 10.79 |
| Bed with Disk promoter | 20.83 | 24.59 | 7.20 | 9.88 |
| bed with Blade promoter | 14.90 | 18.62 | 10.98 | 12.78 |

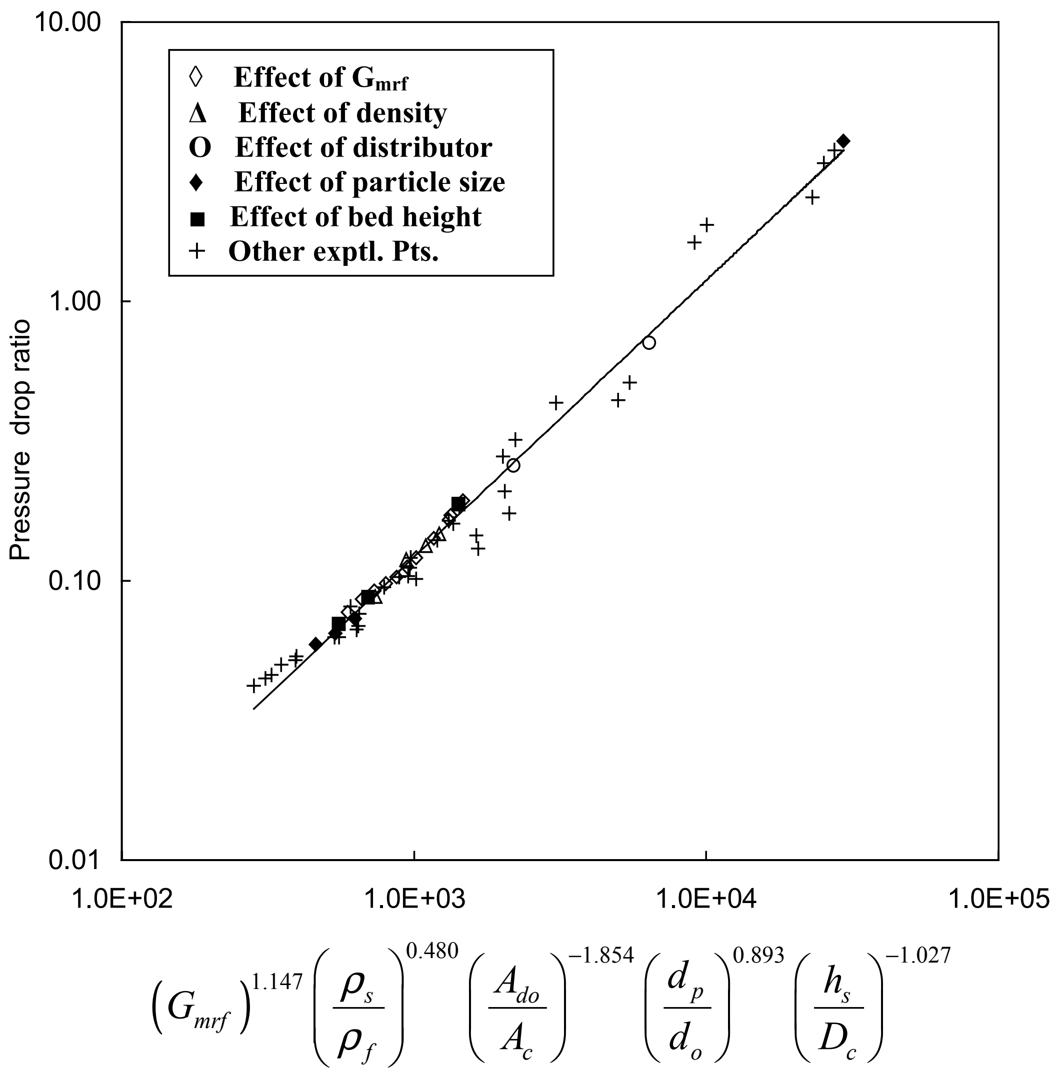
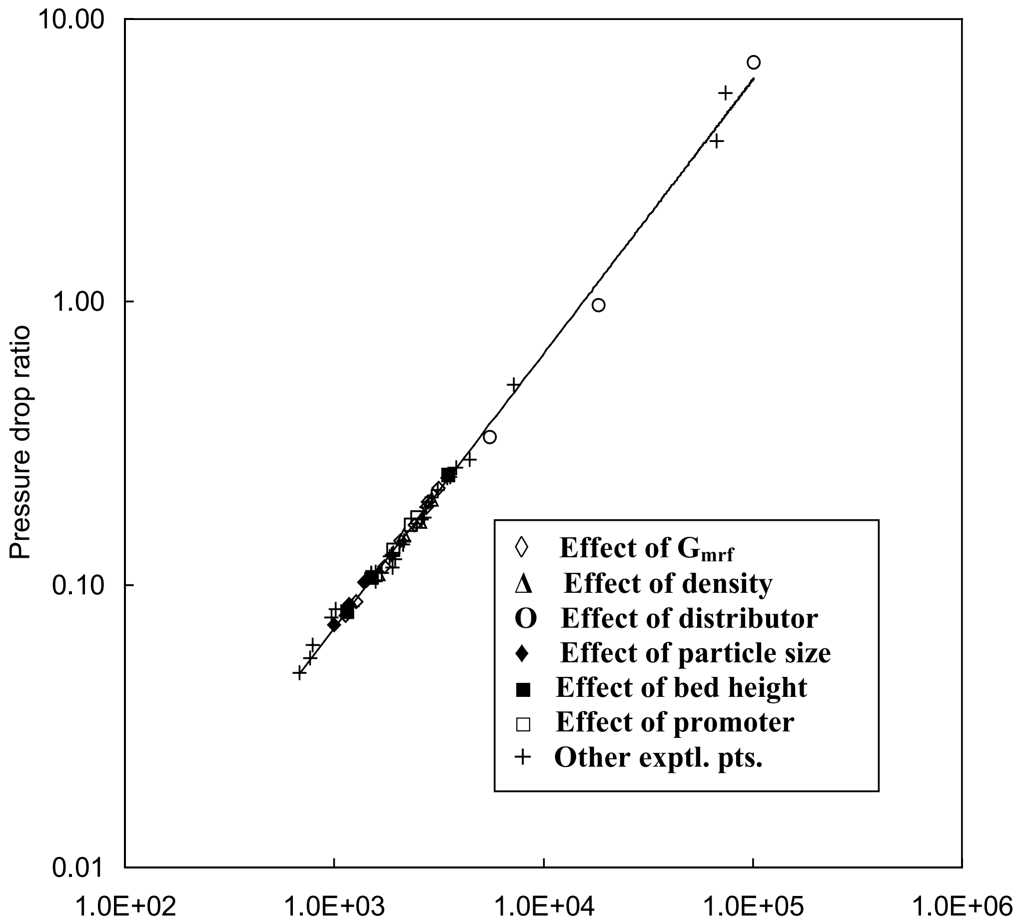



**Fig. 6.1** Variation of distributor-to-bed pressure drop ratio $\left(\frac{\Delta p_d}{\Delta p_b}\right)$ with system parameters for unpromoted bed




$$\left(G_{mrf}\right)^{1.296}\left(\frac{\rho_s}{\rho_f}\right)^{0.550}\left(\frac{A_{do}}{A_c}\right)^{-2.068}\left(\frac{d_p}{d_o}\right)^{0.972}\left(\frac{h_s}{D_c}\right)^{-1.219}\left(\frac{D_e}{D_c}\right)^{-0.213}$$

**Fig. 6.2** Variation of distributor-to-bed pressure drop ratio $\left(\frac{\Delta p_d}{\Delta p_b}\right)$ with system parameters for bed with rod promoter

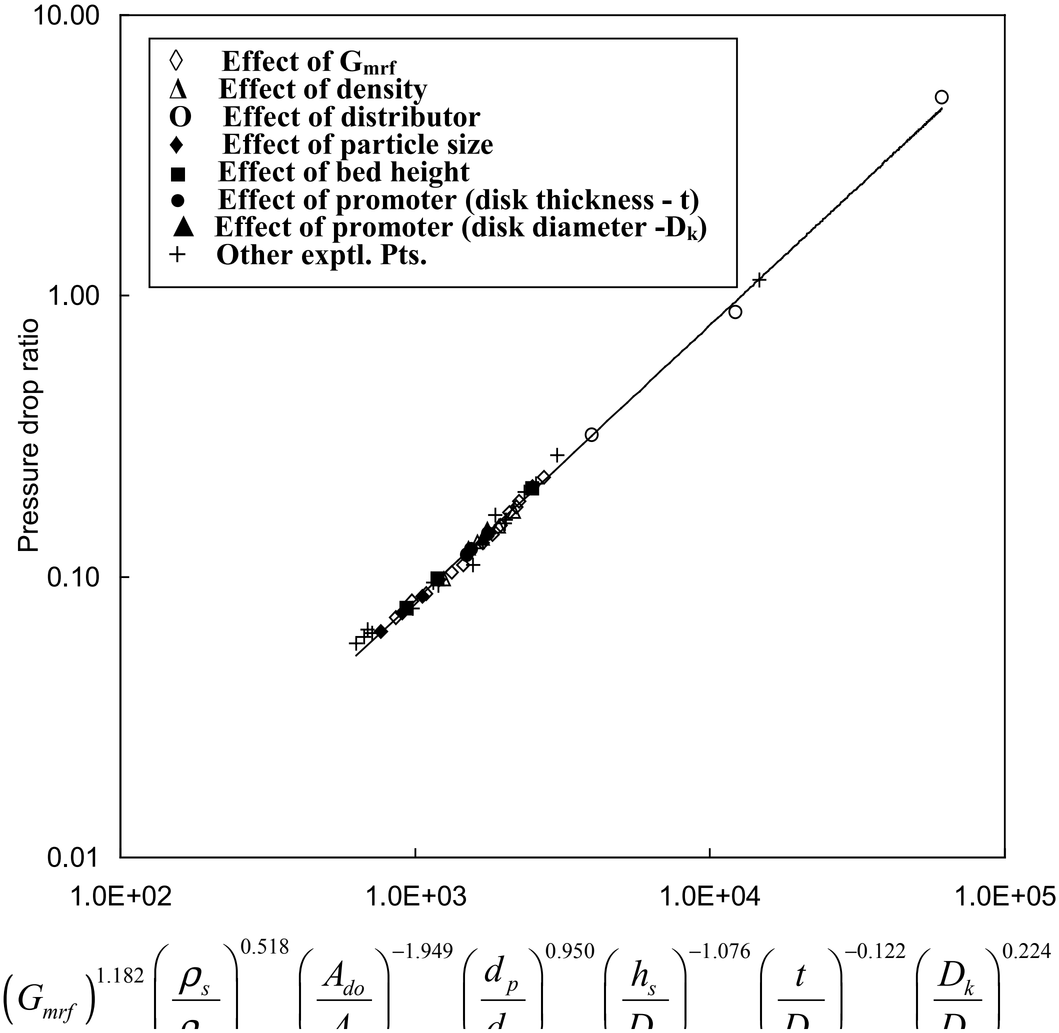
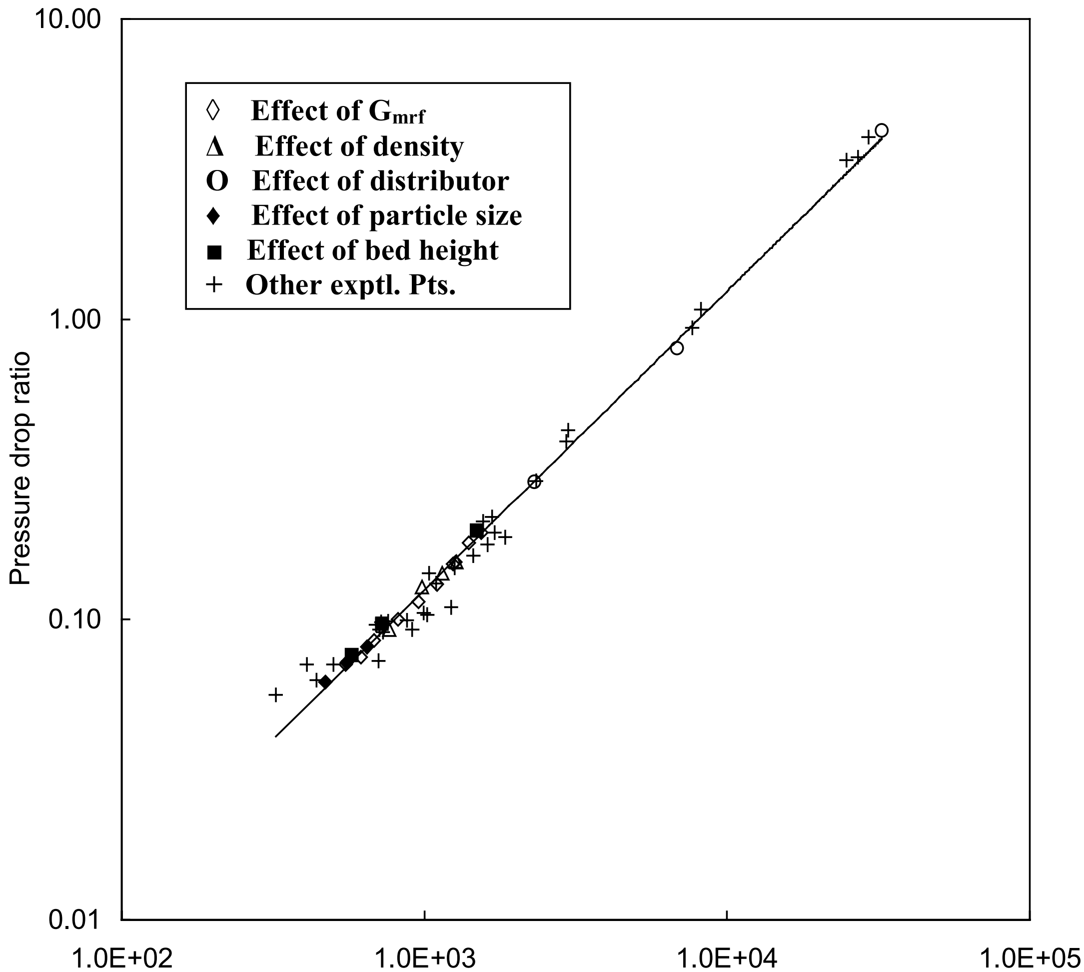



**Fig. 6.3** Variation of distributor-to-bed pressure drop ratio $\left(\frac{\Delta p_d}{\Delta p_b}\right)$ with system parameters for bed with disk promoter




$$\left(G_{mrf}\right)^{1.177}\left(\frac{\rho_s}{\rho_f}\right)^{0.482}\left(\frac{A_{do}}{A_c}\right)^{-1.881}\left(\frac{d_p}{d_o}\right)^{0.926}\left(\frac{h_s}{D_c}\right)^{-1.041}$$

**Fig. 6.4** Variation of distributor-to-bed pressure drop ratio $\left(\frac{\Delta p_d}{\Delta p_b}\right)$ with system parameters for bed with blade promoter

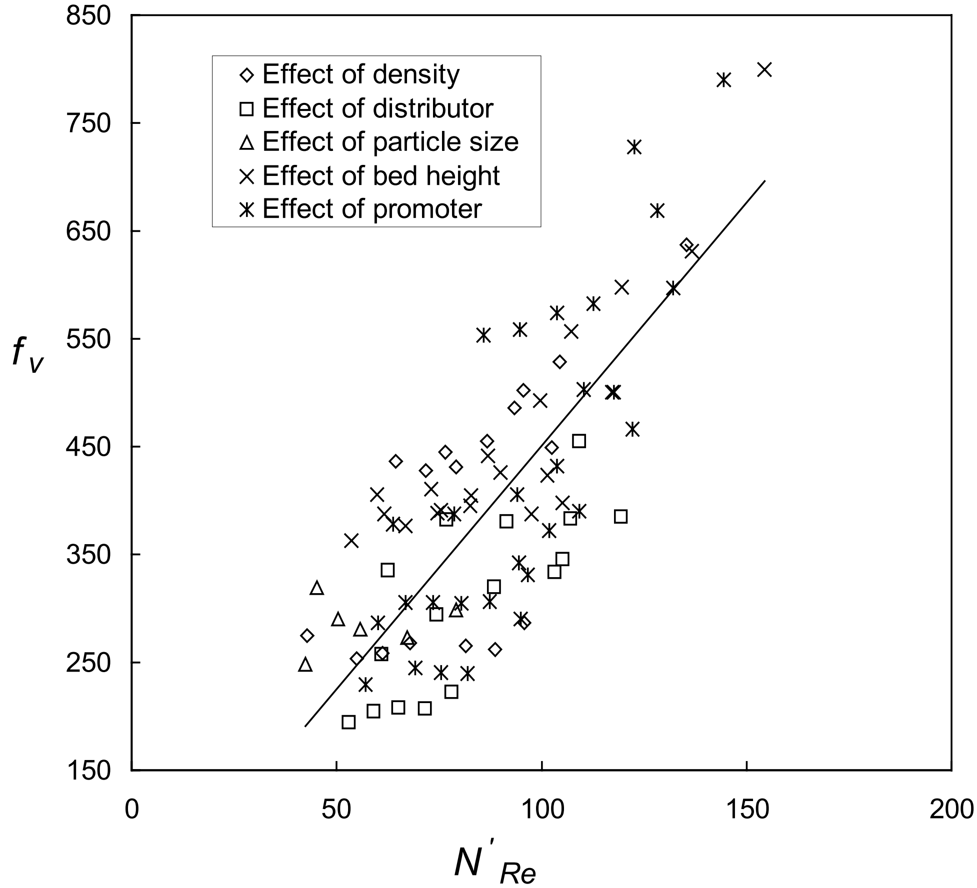



**Fig. 6.5** Variation of $f_v$ versus $N'_{Re}$ for bed with rod promoter

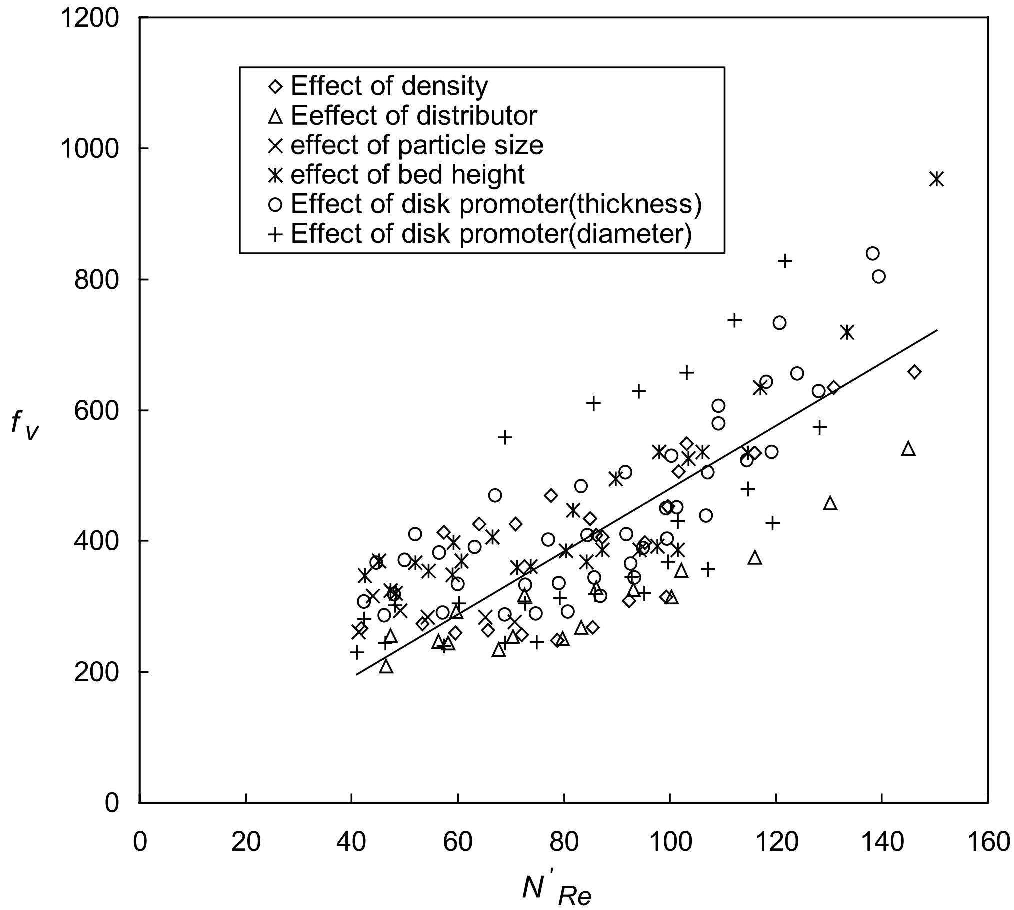



**Fig. 6.6** Variation of $f_v$ versus $N'_{Re}$ for bed with disk promoter

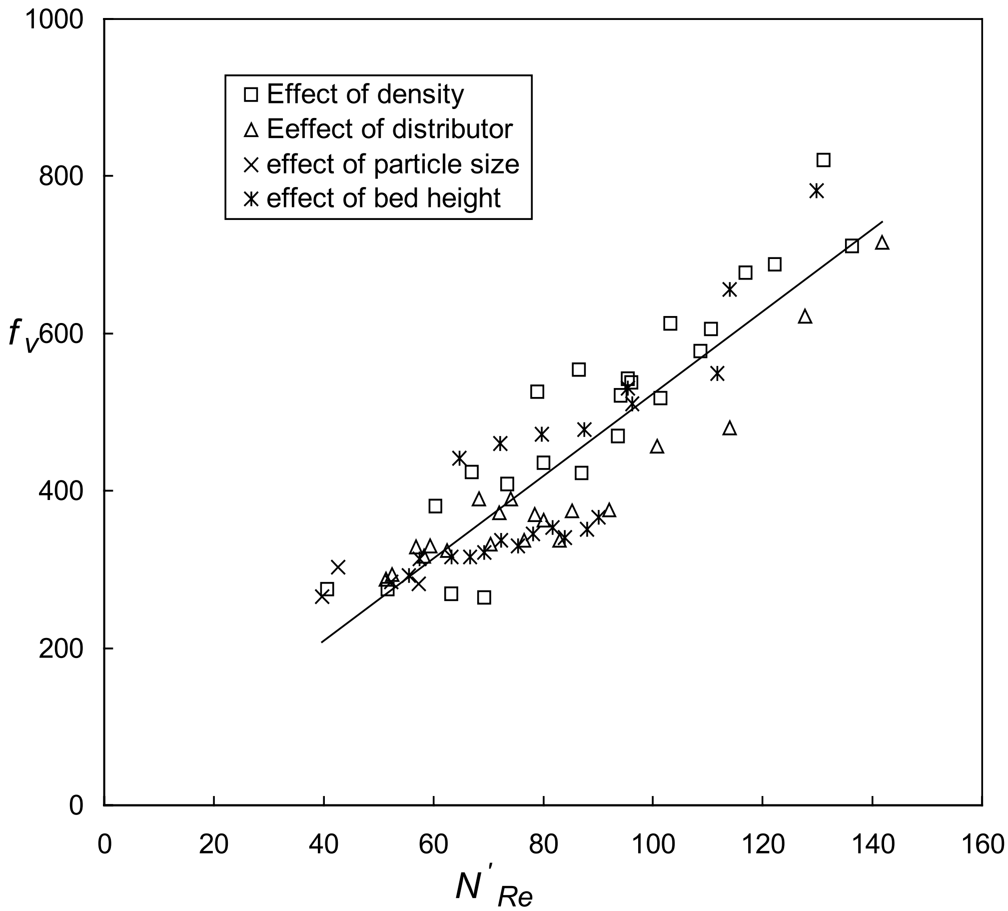



**Fig. 6.7** Variation of $f_v$ versus $N'_{Re}$ for bed with blade promoter

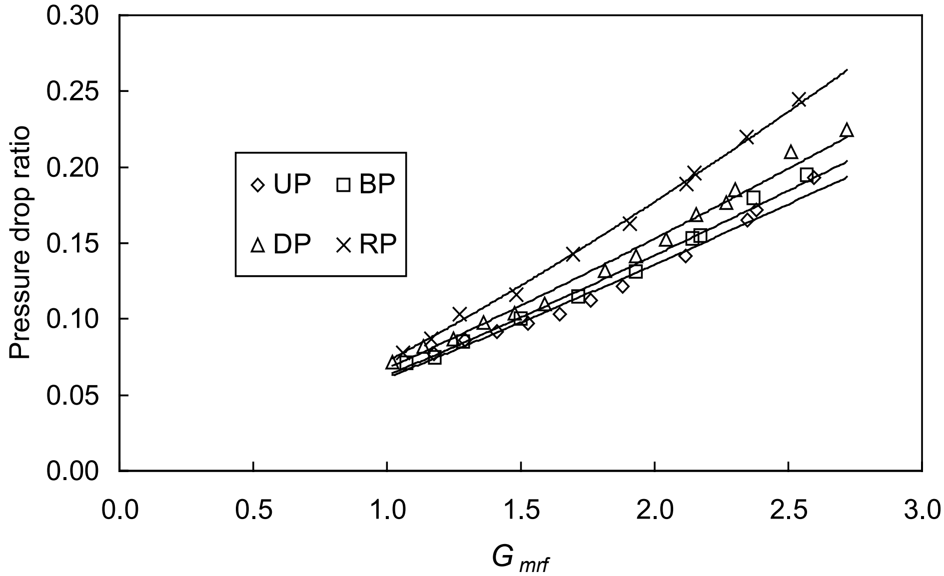



**Fig. 6.8** Variation of distributor-to-bed pressure drop ratio with flow parameter ($G_{mrf}$) for different beds

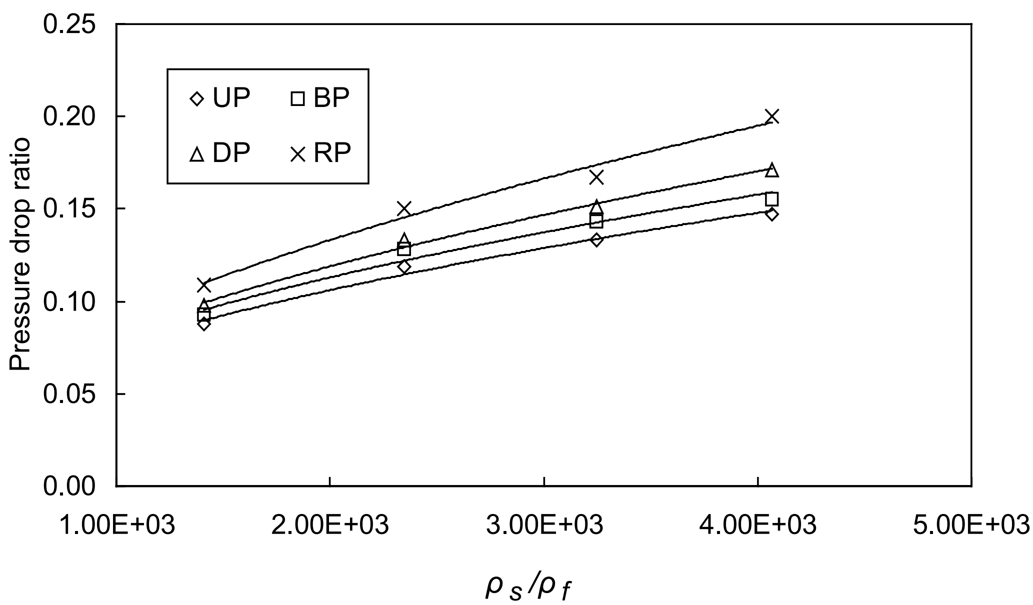



**Fig. 6.9** Variation of distributor-to-bed pressure drop ratio with flow parameter ($G_{mrf}$) for different beds

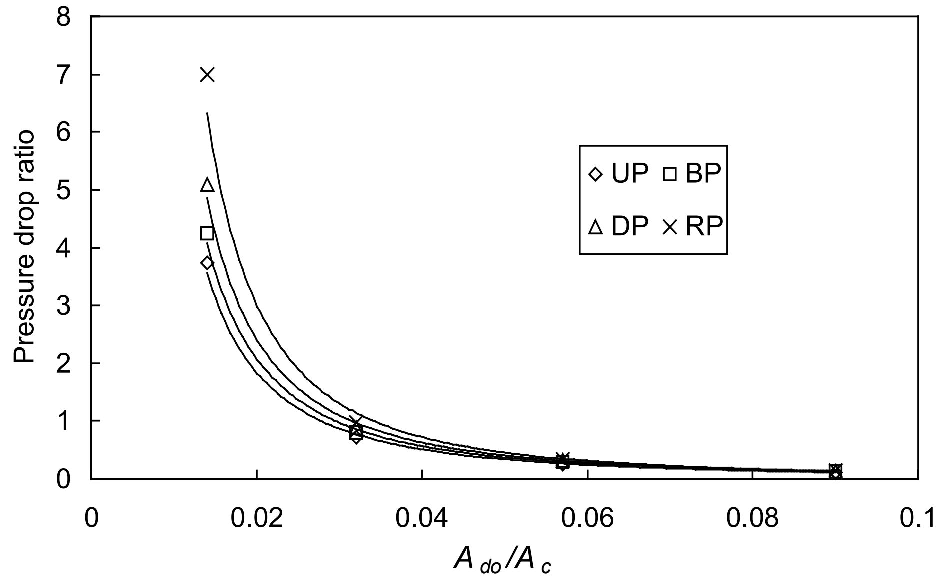



**Fig. 6.10** Variation of distributor-to-bed pressure drop ratio with distributor parameter $(A_{do}/A_c)$ for different beds

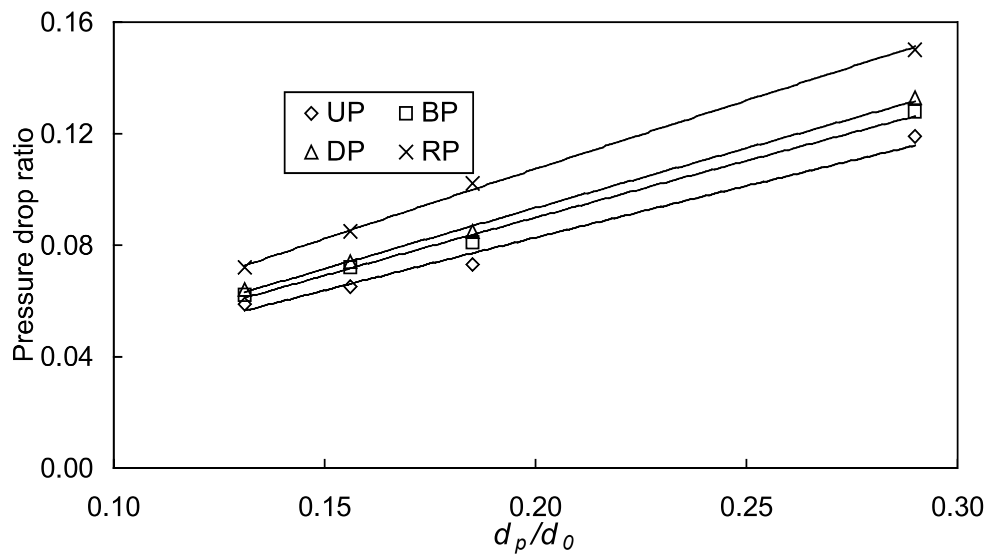



**Fig. 6.11** Variation of distributor-to-bed pressure drop ratio with Particle size parameter $(d_p/d_o)$ for different beds

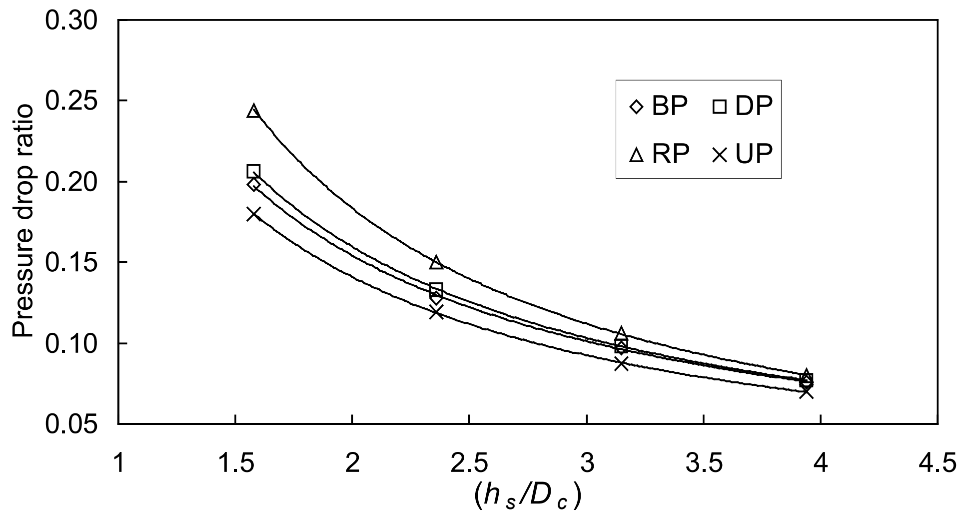



**Fig. 6.12** Variation of distributor-to-bed pressure drop ratio with bed height parameter $(h_s / D_c)$ for different beds

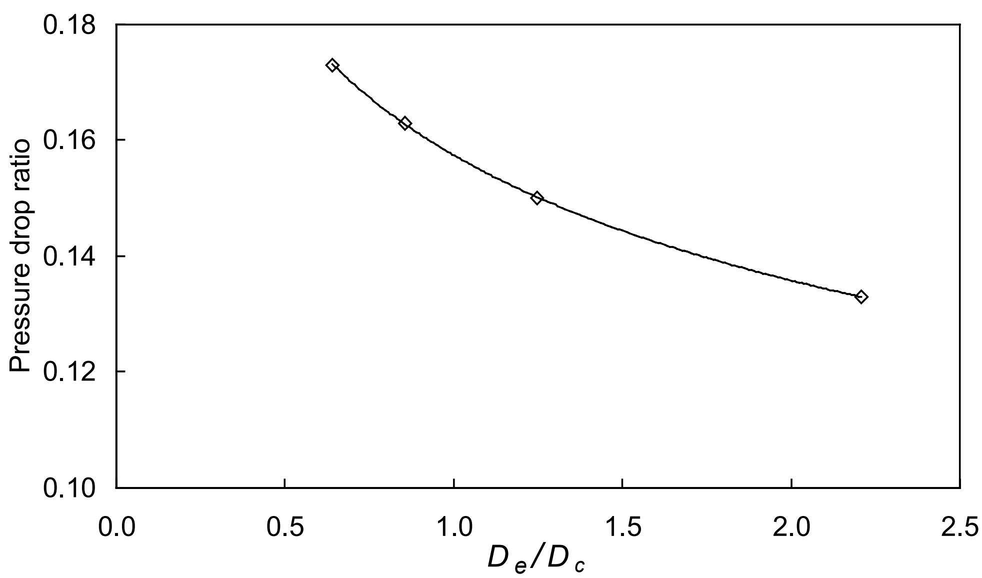



**Fig. 6.13** Variation of distributor-to-bed pressure drop ratio with rod promoter parameter $(D_e / D_c)$ for different beds

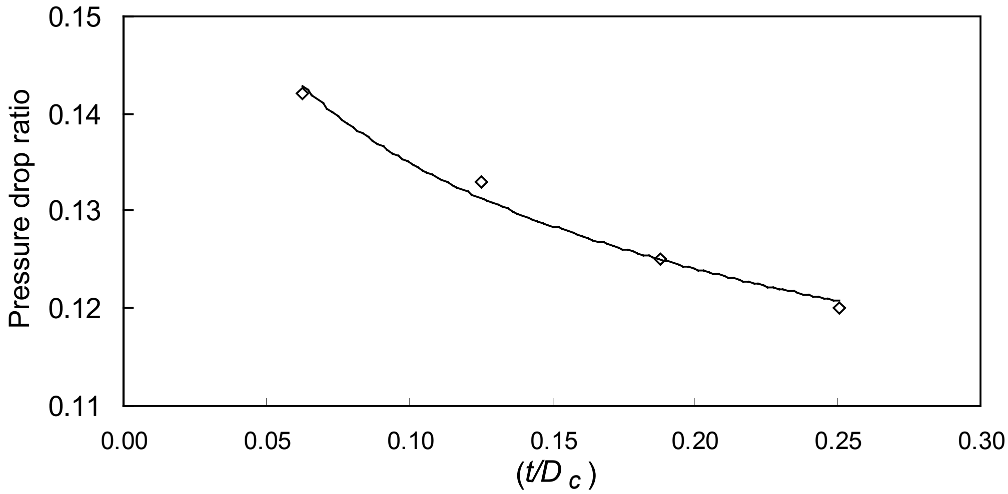



**Fig. 6.14** Variation of distributor-to-bed pressure ratio ($\Delta p_d/\Delta p_b$) with disk thickness parameter (t/Dc) for bed with disk promoter

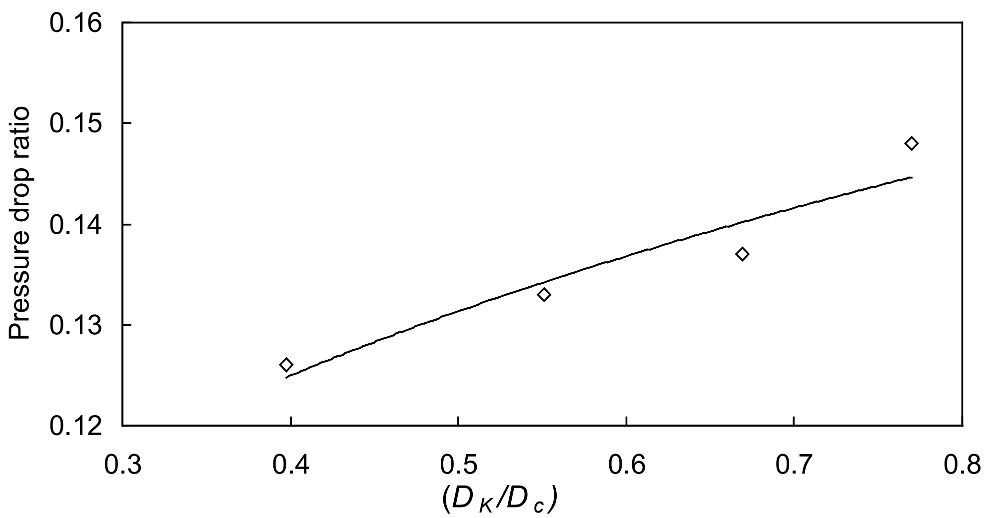



**Fig. 6.15** Variation of distributor-to-bed pressure drop ratio ($\Delta p_d/\Delta p_b$) with disk diameter parameter ($D_k$/Dc) for bed with disk promoter

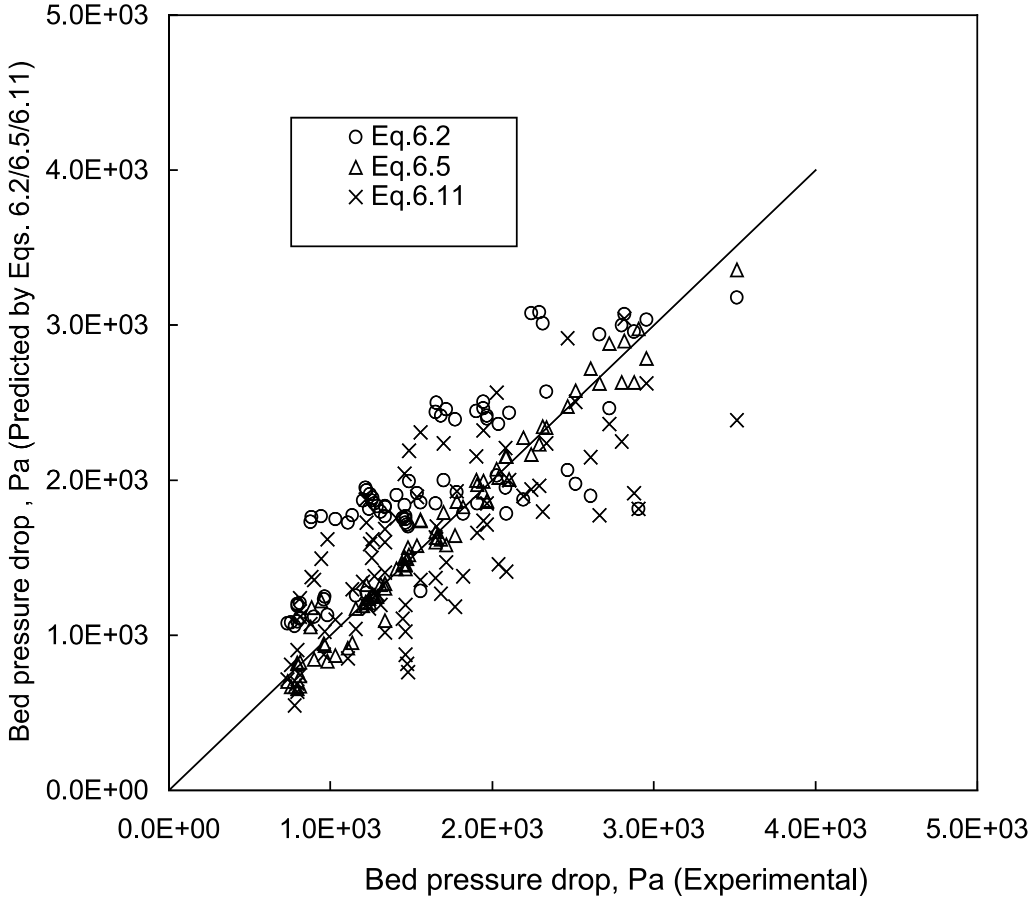



**Fig. 5.16** Comparison between experimental and predicted values of bed pressure drop ($\Delta p_b$) for bed with rod promoter

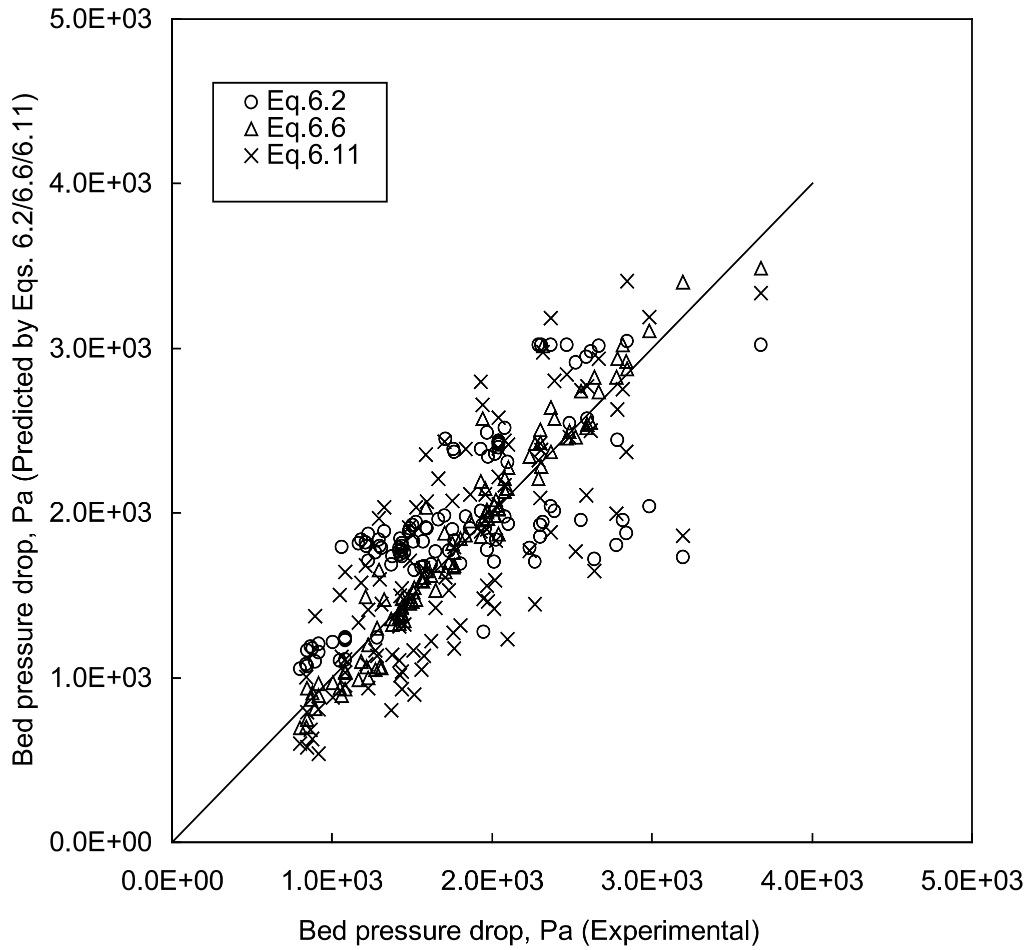



**Fig. 6.17** Comparison between experimental and predicted values of bed pressure drop ($\Delta p_b$) for bed with disk promoter

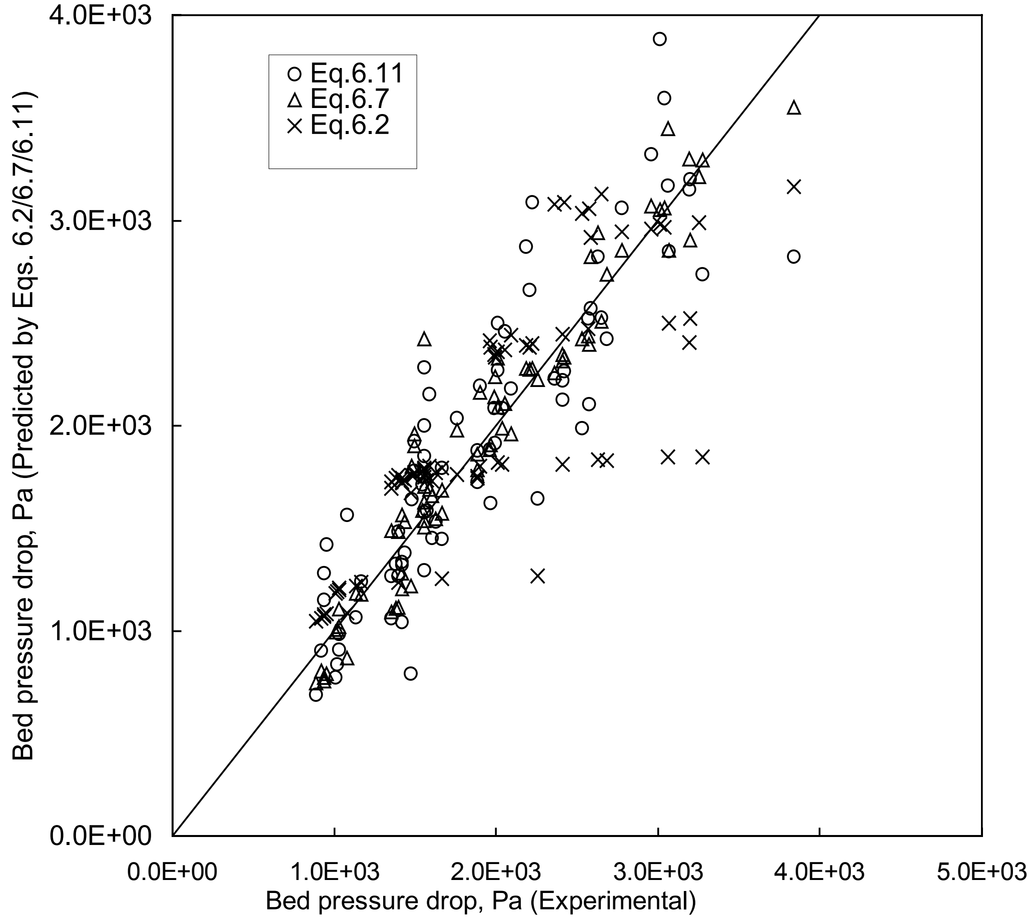



**Fig. 6.18** Comparison between experimental and predicted values of bed pressure drop ($\Delta p_b$) for bed with blade promoter

# CHAPTER VII

# Minimum fluidization velocity in beds with co-axial rod and disk promoter

## 7.1 Introduction

When a fluid passes upward at a velocity through interstices of a bed of solid particle such that there is no movement of the particles, the bed thus formed is termed as a fixed bed. With further increase in the velocity of fluid, the entire bed of solid is suspended and behaves as if its weight is counterbalanced by the buoyant force. At this point, the bed of solids starts behaving like a fluid. This is called onset of fluidization and the velocity of fluid at which this happens, is called minimum fluidization velocity. Prediction of minimum fluidization velocity is one of the most important parameters for the design of fluidizers. It not only sets the lower limit of gas flow rate to the fluidized bed but is also useful for the prediction of bed expansion and fluctuation in the fluidized bed, heat and mass transfer rates, in the analysis of the kinetic data and for the calculation of bed pressure drop at minimum fluidization condition.

Several methods are in use for determining the minimum fluidization velocity, such as measurement of pressure drop through the fixed bed of solid particle, and observing the point at which first bubble appears and the change in heat transfer coefficient with gas velocity. Chiba et al. [1] measured the values of minimum fluidization velocity for binary systems by defluidizing quickly for maximum possible packed bed and well-mixed condition. However Chyang et al. [2] observed for the case of mixed particle system or wide-cut particles, that the defluidization process for measuring the pressure drop at different values of gas velocity will cause particle segregation and affect the profile of pressure drop versus gas velocity. In this present investigation, measurement of pressure drop through the promoted fixed bed was used for the determination of minimum fluidization velocity.

A plot of pressure drop versus gas velocity normally yields a straight line in the fixed bed region. When the pressure drop equals to the weight of the bed per unit area, the bed becomes fluidized. The peak value of the pressure drop in the plot of bed pressure drop against fluid mass velocity on log-log coordinates, corresponds to minimum fluidization velocity.

Singh [3] studied the effect column geometry (viz. square, hexagonal and semicylindrical configuration) on minimum fluidization velocity and observed that the minimum fluidization mass velocity $\left(G_{mf}\right)$ was the least in case of a square column and was maximum in case of cylindrical bed. The value of minimum fluidization velocity in case of semi-cylindrical bed was found to be more than that of hexagonal bed but less than that of cylindrical one. Balakrishnan and Rao [4] in their studies for the effect of radiating screen baffles (promoters), concentric screen cylinder baffles and horizontal screen disk baffles on minimum fluidization velocity observed higher minimum fluidization velocity in baffled beds compared to unbaffled (unpromoted) ones. They concluded that the horizontal screen disk baffles, due to their transverse arrangement, facilitate smooth fluidization, with negligible channeling and slugging as compared to radiating screen and concentric screen cylinder baffles.

In the present work, the rod and the disk promoters of varying configurations and specifications have been used to study the effects of promoters on minimum fluidization velocity in case of gas-fluidized beds compared to unpromoted ones using bed material of varying particle size and density and initial static bed height. The scope of the present investigation has been presented in Table 7.1.

## 7.2 Theoretical analysis

Based on drag force consideration, Davies and Richardson [5] and Pillai and Rao [6] gave the following expression for minimum fluidization mass velocity:

$$G_{mf} = Cd_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f \qquad (7.1)$$

where the constant C depends on particle size, shape, density and its orientation in the bed . Later, Eq. 7.1 was modified by Balakrishnan and Raja Rao [4]. In a solid-fluid system, the increase in minimum fluidization mass velocity observed in a promoted bed can be attributed to the presence of promoters, and Eq. 7.1 can be modified as under considering the particle shape factor:

$$G'_{mf} = C'\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f \tag{7.2}$$

The value of constant $C'$ depends on the promoter parameters in addition to particle and bed properties. From Eqs. 7.1 and 7.2, minimum fluidization mass velocity in promoted beds over unpromoted ones can be expressed as:

$$G'_{mf} - G_{mf} = \left(C' - C\right)\left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \tag{7.3}$$

$$\text{Or, } C' - C = \frac{\left(G'_{mf} - G_{mf}\right)}{\left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right]} = \text{f (promoter parameters)} \tag{7.4}$$

Eq. 7.4 has been expressed in terms of present promoter parameters as under:

For beds with rod promoter

$$C' - C = \frac{\left(G'_{mf} - G_{mf}\right)}{\left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right]} = f_1\left(\frac{D_e}{D_c}\right) = C_1\left(\frac{D_e}{D_c}\right)^{n_1} \tag{7.5}$$

And, for beds with disk promoters

$$C' - C = \frac{\left(G'_{mf} - G_{mf}\right)}{\left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right]} = f_2\left(\frac{t}{D_c}, \frac{D_k}{D_c}\right)$$

$$= C_2\left[\left(\frac{t}{D_c}\right)^{n_2}\left(\frac{D_k}{D_C}\right)^{n_3}\right]^{n_4} \tag{7.6}$$

The exponents $n_1$, $n_2$, $n_3$, $n_4$ and constants $C_1$ and $C_2$ have been obtained from $\frac{\left(G'_{mf} - G_{mf}\right)}{\left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right]}$ versus respective promoter parameter plots. Thus, the final correlations obtained from Figs. 7.1 and 7.2 are as follows:

For bed with rod promoter

$$\frac{\left(G'_{mf} - G_{mf}\right)}{\left[\phi_s{}^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right]} = \left(C' - C\right) = 0.0001\left(\frac{D_e}{D_c}\right)^{-0.48} \tag{7.7}$$

which on rearrangement gave

$$G'_{mf} = \left[C + 0.0001\left(\frac{D_e}{D_c}\right)^{-0.48}\right] \times \left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \tag{7.8}$$

**For bed with disk promoter**

$$\frac{\left(G'_{mf} - G_{mf}\right)}{\left[\phi_s{}^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right]} = \left(C' - C\right) = 3 \times 10^{-5}\left(\frac{t}{D_c}\right)^{-0.88}\left(\frac{D_k}{D_c}\right)^{2.80} \tag{7.9}$$

and on rearrangement

$$G'_{mf} = \left[C + 3 \times 10^{-5}\left(\frac{t}{D_c}\right)^{-0.88}\left(\frac{D_k}{D_c}\right)^{2.80}\right] \times \left[\phi_s^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \tag{7.10}$$

From the fluidization of unpromoted beds with varying particle size and density, the value of C has been found to vary from 0.000698 to 0.000983. An average value of C=0.000829 has been taken in the present work. Substituting for C in Eqs. 7.8 and 7.10, the proposed final correlations for predicting minimum fluidization mass velocity become:

For bed with rod promoter

$$G'_{mf} = \left[0.000289 + 0.0001\left(\frac{D_e}{D_c}\right)^{-0.48}\right] \times \left[\phi_s{}^2 d_p^2 \rho_f \left(\rho_s - \rho_f\right) g / \mu_f\right] \tag{7.11}$$

and for bed with disk promoter

$$G'_{mf} = \left[ 0.000829 + 3\times10^{-5} \left( \frac{t}{D_c} \right)^{-0.88} \left( \frac{D_k}{D_c} \right)^{2.80} \right]$$

$$\times \phi_s^2 d_p^2 \rho_f \left( \rho_s - \rho_f \right) g / \mu_f \qquad (7.12)$$

## 7.3 Results and Discussion

An average value of the constant, C=0.000829 obtained experimentally in unpromoted fluidized beds with materials of varied size and density, has been found to be comparable with the values of 0.00078, 0.000701, and 0.000691 as reported by Davies and Richardson [4], Pillai and Rao [5], and Balakrishnan and Raja Rao [6] respectively. The reason for little higher value of C than those reported might be because of multiorifice distributor used in the present study as against wire mesh distributor used by the earlier investigators. The variation of bed pressure drop versus $G_f$ plots (Figs. 7.3 to 7.5) for different beds shows the relative increase in minimum fluidization mass velocity in promoted beds over the unpromoted ones. The predicted values of minimum fluidizing mass velocity in case of unpromoted as well as promoted beds with rod and disk promoters using the developed correlations have been given with their deviations from experimental ones respectively in Tables 7.2 to 7.4. The comparison plots (Figs. 7.6 and 7.7) show fair agreement between the experimental and the calculated values of minimum fluidizing mass velocity. The increase in minimum fluidizing mass velocity for the promoted beds over unpromoted ones have been shown in Table 7.5.

The mean and the standard deviations in case of unpromoted as well as the promoted beds have been given in Table 7.6.

## 7.4 Conclusion

The developed correlations can be used satisfactorily to predict the minimum fluidization mass velocity in promoted gas-solid fluidized beds with rod and disk promoters. From the proposed correlations and the comparison of the experimental and predicted values of minimum fluidization mass velocity for promoted as well as unpromoted beds (Tables 7.2 to 7.4), it is evident that the minimum fluidization mass velocity is higher in promoted beds compared to conventional unpromoted ones. This is in agreement with the findings of Balakrishnan and Raja Rao [4]. Also, it can be concluded that the minimum fluidization mass velocity in a promoted fluidized bed with rod promoter is higher than that in promoted fluidized bed with disk promoter for the same blockage area. A rod promoter can increase the minimum fluidization mass velocity to a maximum of about 15% whereas a disk promoter can enhance to a maximum of about 11% depending upon the configuration and other specifications. Further, it can be observed that in case of beds with rod promoter, the values of minimum fluidization mass velocity increases with increase in the number of radial rods. For the case of beds with disk promoter, the minimum fluidization mass velocity has been found to increase with decrease in disk thickness and increase in disk diameter. The combined effect of disk thickness and disk diameter is to increase the minimum fluidization mass velocity over the conventional unpromoted bed. Thus, the developed correlations can be used satisfactorily to predict the minimum fluidization mass velocity for the promoted gas-solid fluidized beds with rod and disk promoters in the range of the present experimental limits.

## Nomenclature

| | |
|---|---|
| $A_o$ | open area in promoted bed with rod promoters, $L^2$ |
| $C_1$, $C_2$ | constants in equations (7.5 and 7.6) |
| $D_c$ | column diameter, L |

| | |
|---|---|
| $D_e$ | equivalent diameter for the promoted bed, $4A_o / P$, L |
| $D_k$ | disk diameter, L |
| $d_p$ | particle size, L |
| f, $f_1$, $f_2$ | functions in term of promoter parameters |
| $G_{mf}$ | minimum fluidization mass velocity in unpromoted beds, $ML^{-2}T^{-1}$ |
| $G'_{mf}$ | minimum fluidization mass velocity in promoted beds, $ML^{-2}T^{-1}$ |
| $g$ | acceleration due to gravity, $LT^{-2}$ |
| M | materials |
| $n_1$-$n_4$ | exponents |
| P | total rod perimeter, m |
| $P_1$-$P_4$ | rod promoters |
| $P_5$-$P_{11}$ | disk promoters |
| $t$ | disk thickness, L |

## Greek letters

| | |
|---|---|
| $\rho_f$ | density of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |
| $\phi_s$ | sphericity |
| $\mu_f$ | viscosity, $ML^{-1} T^{-1}$ |

# References


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**Table 7.1** Scope of the experiments

| A: Bed properties | | | |
|---|---|---|---|
| Materials | $d_p$ x $10^3$ , m | $\rho_s$ x$10^{-3}$ , kg/ $m^3$ | $\phi_s$ |
| Dolomite | 1.125 | 2.817 | 0.7679 |
| Dolomite | 0.725 | 2.817 | 0.6319 |
| Dolomite | 0.463 | 2.817 | 0.8715 |
| Dolomite | 0.39 | 2.817 | 0.9108 |
| Dolomite | 0.328 | 2.817 | 0.9452 |
| Alum | 0.725 | 1.691 | 0.7050 |
| Iron-Ore | 0.725 | 3.895 | 0.6929 |
| Mangnese-Ore | 0.725 | 4.880 | 0.7261 |
| **B: Rod promoter details** | | | |
| Promoter | specifications | | |
| $P_1$ | 1 no. of $\phi$6.1 mm central rod and 4 nos. of $\phi$ 4 mm rods | | |
| $P_2$ | 1 no. of $\phi$6.1 mm central rod and 8 nos. of $\phi$ 4 mm rods | | |
| $P_3$ | 1 no. of $\phi$6.1 mm central rod and 12 nos. of $\phi$ 4 mm rods | | |
| $P_4$ | 1 no. of $\phi$6.1 mm central rod and 16 nos. of $\phi$ 4 mm rods | | |
| **C: Disk promoter details** | | | |
| Promoter specification | $D_k$ x$10^3$, m | $t$ x$10^3$, m | Rod promoters of equal blockage volume as that of disk promoters in column (1) |
| (1) | (2) | (3) | (4) |
| $P_5$ | 28.000 | 3.18 | $P_1$(4)* |
| $P_6$ | 28.000 | 6.36 | $P_2$ (8)* |
| $P_7$ | 28.000 | 9.54 | $P_3$ (12)* |
| $P_8$ | 28.000 | 12.72 | $P_4$ (16)* |
| $P_9$ | 20.260 | 6.36 | $P_1$ |
| $P_{10}$ | 34.000 | 6.36 | $P_3$ |
| $P_{11}$ | 39.125 | 6.36 | $P_4$ |

* nos. of radial rods

**Table 7.2** Comparison between experimental and calculated values of minimum fluidization velocity for unpromoted bed

| Sl. No. | Material | Particle Size, $d_p$ x$10^3$,m | Exptl. values of $G_{mf}$, kg.m$^{-2}$.hr$^{-1}$ | Values of C (using Eq. 7.1) | Calculated values of $G'_{mf}$, kg.m$^{-2}$.hr$^{-1}$ | % Deviation |
|---|---|---|---|---|---|---|
| 1 | Alum | 0.725 | 864 | 0.000840 | 853 | 1.32 |
| 2 | Dolomite | 1.125 | 2444 | 0.000737 | 2748 | -12.46 |
| 3 | Dolomite | 0.725 | 1504 | 0.000740 | 1686 | -12.08 |
| 4 | Dolomite | 0.463 | 878 | 0.000824 | 884 | -0.63 |
| 5 | Dolomite | 0.390 | 729 | 0.000881 | 686 | 5.87 |
| 6 | Dolomite | 0.328 | 618 | 0.000983 | 521 | 15.68 |
| 7 | Fe-Ore | 0.725 | 2125 | 0.000928 | 1898 | 10.69 |
| 8 | Mn-Ore | 0.725 | 2200 | 0.000698 | 2611 | -18.70 |

**Table 7.3** Comparison between experimental and calculated values of minimum fluidization velocity for bed with rod promoter

| Sl. No. | Material | Size, $d_p$ x$10^3$,m | Promoter | Minimum fluidization mass velocity ($G'_{mf}$), kg.m$^{-2}$.hr$^{-1}$ | | % Deviation |
|---|---|---|---|---|---|---|
| | | | | Experimen-tal | Calculated | |
| 1 | Alum | 0.7250 | $P_2$ | 970 | 945 | 2.57 |
| 2 | Dolomite | 1.1250 | $P_2$ | 2933 | 3046 | -3.87 |
| 3 | Dolomite | 0.7250 | $P_1$ | 1700 | 1825 | -7.33 |
| 4 | Dolomite | 0.7250 | $P_2$ | 1732 | 1868 | -7.88 |
| 5 | Dolomite | 0.7250 | $P_3$ | 1788 | 1905 | -6.53 |
| 6 | Dolomite | 0.7250 | $P_4$ | 1854 | 1937 | -4.49 |
| 7 | Dolomite | 0.4625 | $P_2$ | 1000 | 979 | 2.06 |
| 8 | Dolomite | 0.3900 | $P_2$ | 800 | 761 | 4.92 |
| 9 | Dolomite | 0.3275 | $P_2$ | 663 | 578 | 12.88 |
| 10 | Fe-Ore | 0.7250 | $P_2$ | 2400 | 2104 | 12.35 |
| 11 | Mn-Ore | 0.7250 | $P_2$ | 2550 | 2895 | -13.51 |

**Table 7.4** Comparison between experimental and calculated values of minimum fluidization velocity for bed with disk promoter

| Sl. No. | Material | Size, $d_p$ x$10^3$,m | Promoter | Minimum fluidization mass velocity ($G'_{mf}$), kg.m$^{-2}$.hr$^{-1}$ | | % Deviation |
|---|---|---|---|---|---|---|
| | | | | Experimental | Calculated | |
| 1 | Alum | 0.725 | $P_6$ | 900 | 889 | 1.24 |
| 2 | Dolomite | 1.125 | $P_6$ | 2902 | 2865 | 1.27 |
| 3 | Dolomite | 0.725 | $P_5$ | 1653 | 1817 | -9.95 |
| 4 | Dolomite | 0.725 | $P_6$ | 1590 | 1757 | -10.52 |
| 5 | Dolomite | 0.725 | $P_7$ | 1565 | 1736 | -10.91 |
| 6 | Dolomite | 0.725 | $P_8$ | 1540 | 1725 | -11.98 |
| 7 | Dolomite | 0.725 | $P_9$ | 1520 | 1714 | -12.79 |
| 8 | Dolomite | 0.725 | $P_{10}$ | 1600 | 1809 | -13.06 |
| 9 | Dolomite | 0.725 | $P_{11}$ | 1625 | 2868 | -14.98 |
| 10 | Dolomite | 0.463 | $P_6$ | 957 | 921 | 3.75 |
| 11 | Dolomite | 0.390 | $P_6$ | 740 | 715 | 3.33 |
| 12 | Dolomite | 0.328 | $P_6$ | 559 | 543 | 2.81 |
| 13 | Fe-Ore | 0.725 | $P_6$ | 2200 | 1979 | 10.07 |
| 14 | Mn-Ore | 0.725 | $P_6$ | 2300 | 2722 | -18.36 |

**Table 7.5** Increase in minimum fluidizing velocity of promoted beds over corresponding unpromoted beds

| Sl. No. | Material | Size, $d_p$ x10$^3$,m | Promoter | Minimum fluidizing mass velocity, kg.m$^{-2}$.hr$^{-1}$ | | % Increase over un-promoted |
|---|---|---|---|---|---|---|
| | | | | $G_{mf}$ | $G'_{mf}$ | |
| 1 | Alum | 0.725 | $P_2$ | 853 | 945 | 10.79 |
| 2 | Alum | 0.725 | $P_6$ | 853 | 889 | 4.21 |
| 3 | Dolomite | 1.125 | $P_2$ | 2748 | 3046 | 10.84 |
| 4 | Dolomite | 1.125 | $P_6$ | 2748 | 2865 | 4.26 |
| 5 | Dolomite | 0.725 | $P_1$ | 1686 | 1825 | 8.25 |
| 6 | Dolomite | 0.725 | $P_2$ | 1686 | 1868 | 10.80 |
| 7 | Dolomite | 0.725 | $P_3$ | 1686 | 1905 | 13.00 |
| 8 | Dolomite | 0.725 | $P_4$ | 1686 | 1937 | 14.90 |
| 9 | Dolomite | 0.725 | $P_5$ | 1686 | 1818 | 7.80 |
| 10 | Dolomite | 0.725 | $P_6$ | 1686 | 1757 | 4.23 |
| 11 | Dolomite | 0.725 | $P_7$ | 1686 | 1736 | 2.95 |
| 12 | Dolomite | 0.725 | $P_8$ | 1686 | 1725 | 2.29 |
| 13 | Dolomite | 0.725 | $P_9$ | 1686 | 1714 | 1.68 |
| 14 | Dolomite | 0.725 | $P_{10}$ | 1686 | 1809 | 7.29 |
| 15 | Dolomite | 0.725 | $P_{11}$ | 1686 | 1868 | 10.82 |
| 16 | Dolomite | 0.463 | $P_2$ | 884 | 979 | 10.75 |
| 17 | Dolomite | 0.463 | $P_6$ | 884 | 921 | 4.20 |
| 18 | Dolomite | 0.390 | $P_2$ | 686 | 761 | 10.93 |
| 19 | Dolomite | 0.390 | $P_6$ | 686 | 715 | 4.28 |
| 20 | Dolomite | 0.328 | $P_2$ | 521 | 578 | 10.94 |
| 21 | Dolomite | 0.328 | $P_6$ | 521 | 543 | 4.28 |
| 22 | Fe-Ore | 0.725 | $P_2$ | 1898 | 2104 | 10.85 |
| 23 | Fe-Ore | 0.725 | $P_6$ | 1898 | 1979 | 4.24 |
| 24 | Mn-Ore | 0.725 | $P_2$ | 2611 | 2895 | 10.88 |
| 25 | Mn-Ore | 0.725 | $P_6$ | 2611 | 2722 | 4.26 |

**Table 7.6** Mean and standard deviations

| Bed particulars | Mean deviation | Standard deviation |
|---|---|---|
| Un-promoted | 9.68 | 12.15 |
| Bed with rod promoter | 7.13 | 8.50 |
| Bed with disk promoter | 8.93 | 8.65 |

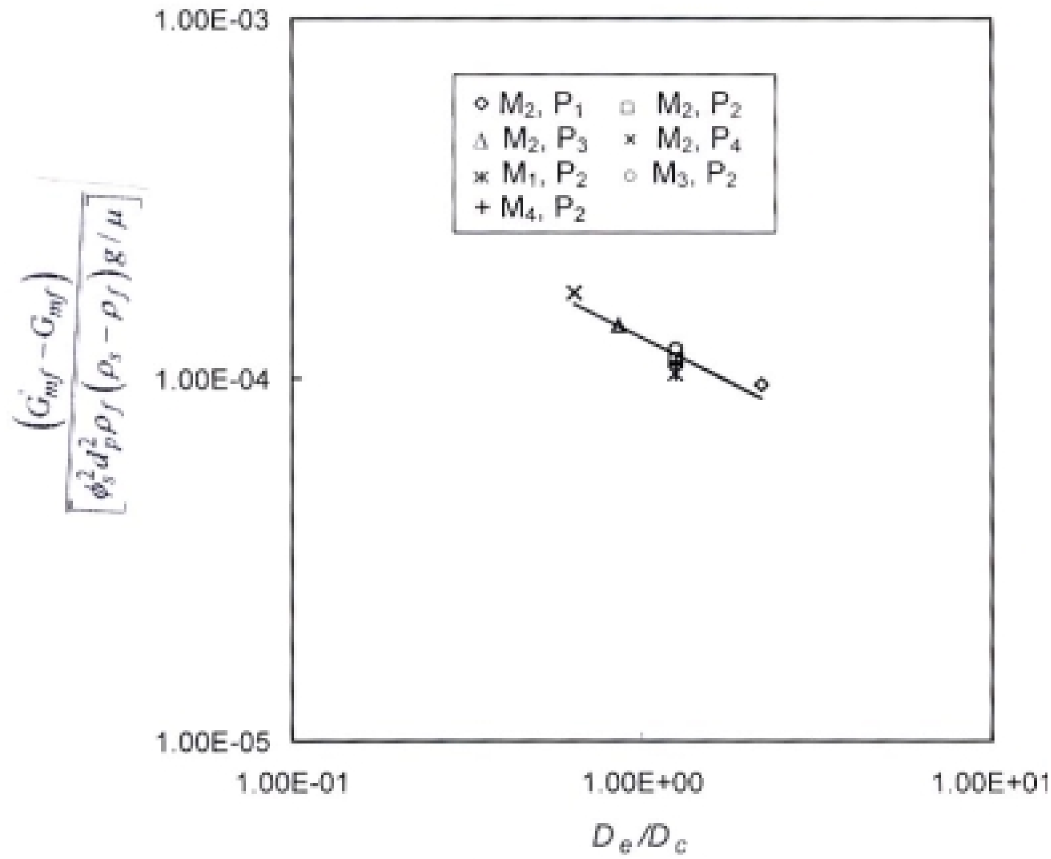


**Fig. 7.1** Variation of $\frac{(G'_{mf} - G_{mf})}{[\phi_s^2 d_p^2 \rho_f (\rho_s - \rho_f) g / \mu]}$ with rod promoter

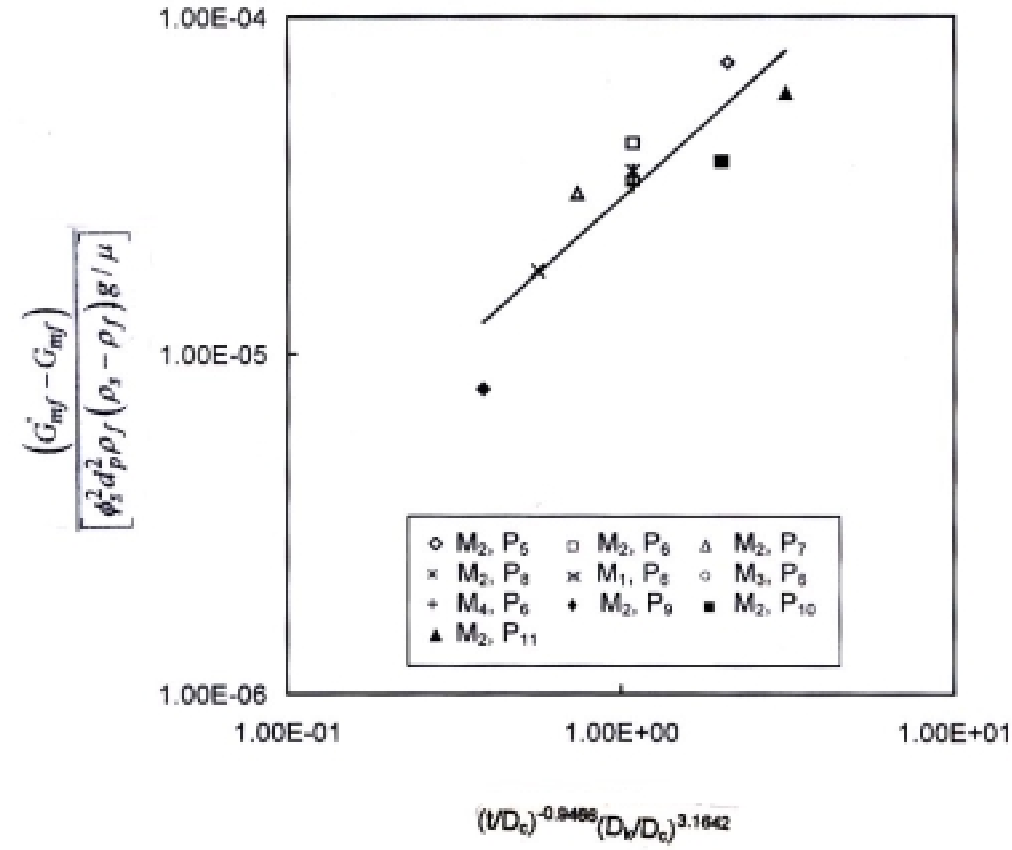


**Fig. 7.2** Variation of $\frac{(G'_{mf} - G_{mf})}{[\phi_s^2 d_p^2 \rho_f (\rho_s - \rho_f) g / \mu]}$ With disk promoter parameters

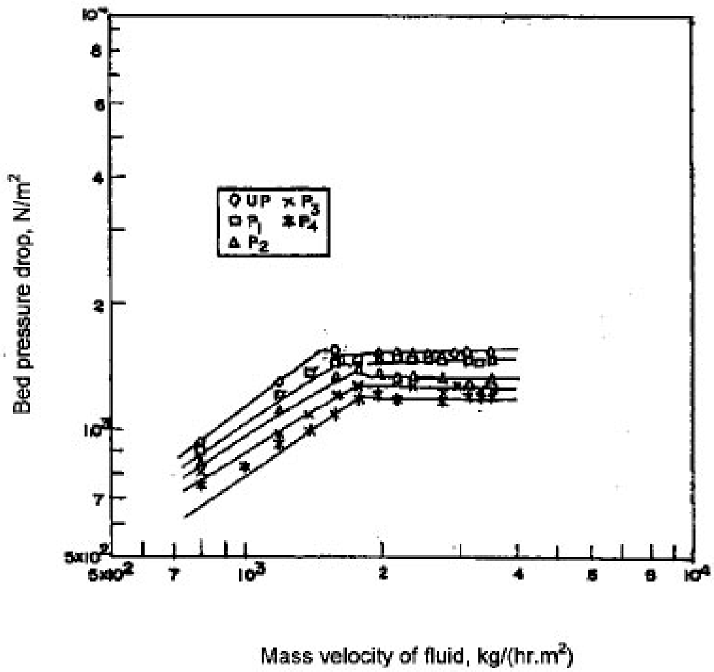


Fig. 7.3 Variation of bed pressure drop $(\Delta p_b)$ with mass velocity of fluid $(G_f)$ for unpromoted bed and beds with disk promoter (varying disk thickness)

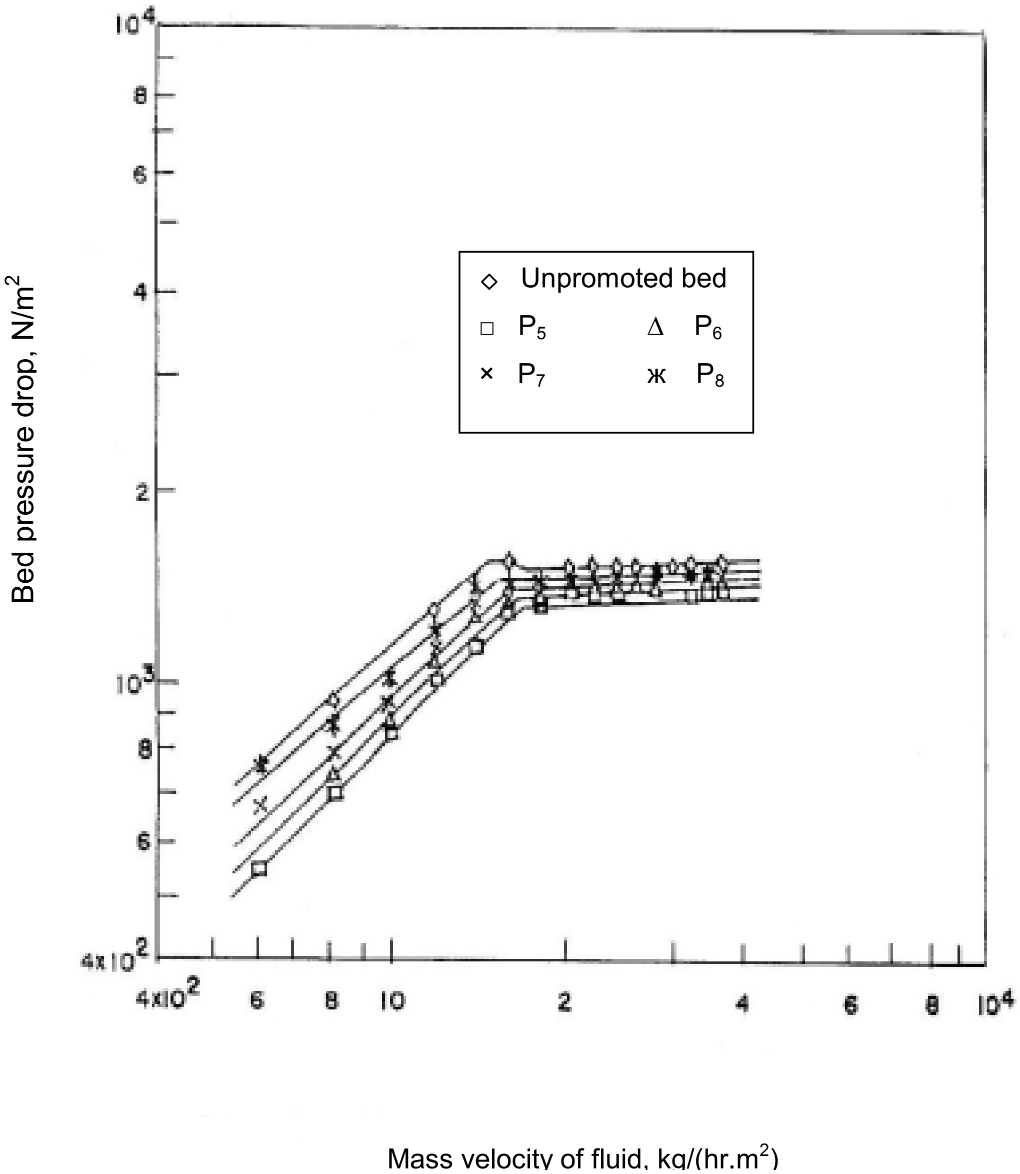


**Fig. 7.4** Variation of bed pressure drop $(\Delta p_b)$ with mass velocity of fluid $(G_f)$ for unpromoted bed and beds with disk promoter (varying disk thickness)

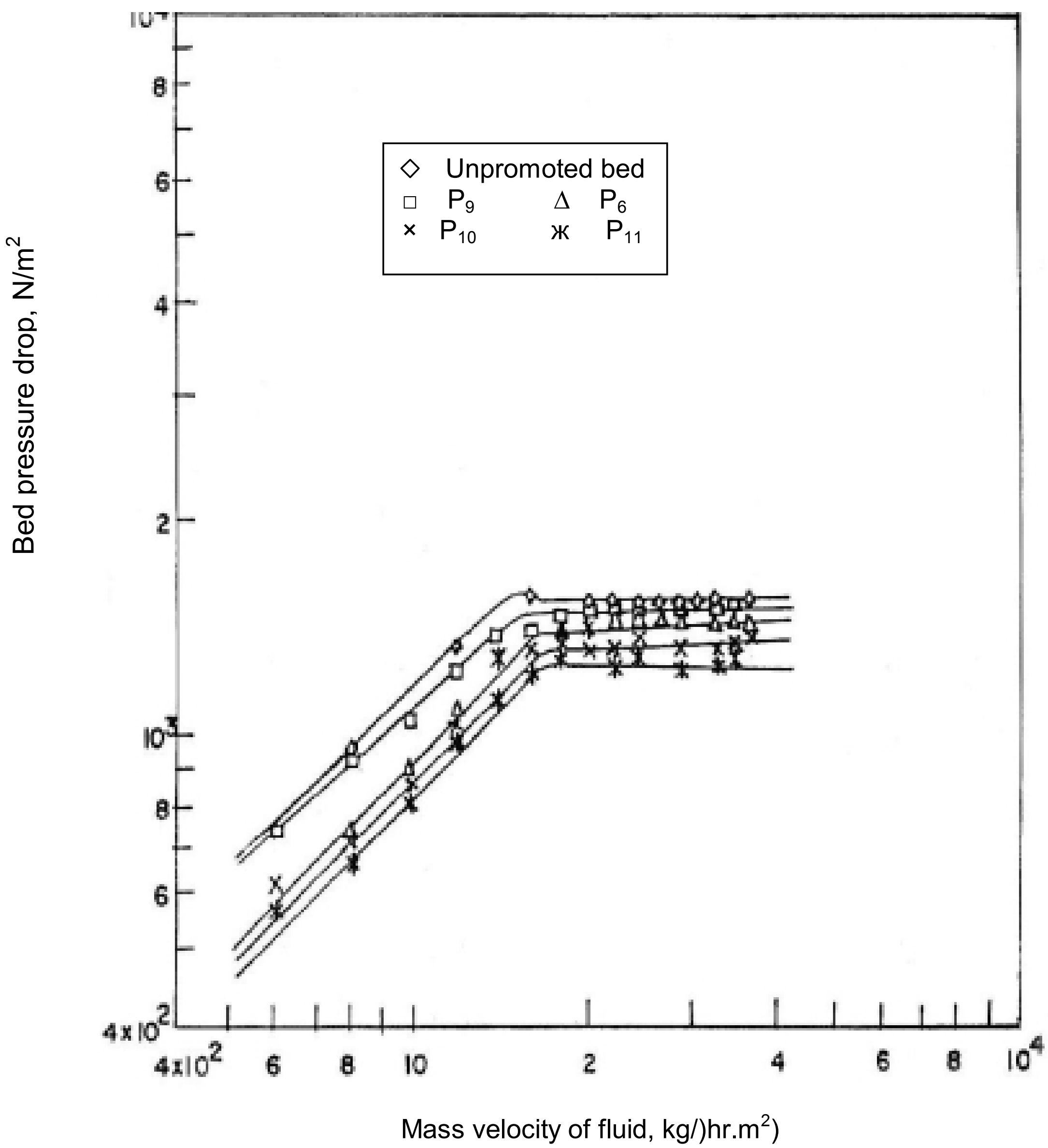


**Fig. 7.5** Variation of bed pressure drop $(\Delta p_b)$ with mass velocity of fluid $(G_f)$ for unpromoted bed and beds with disk promoter (varying disk diameter)

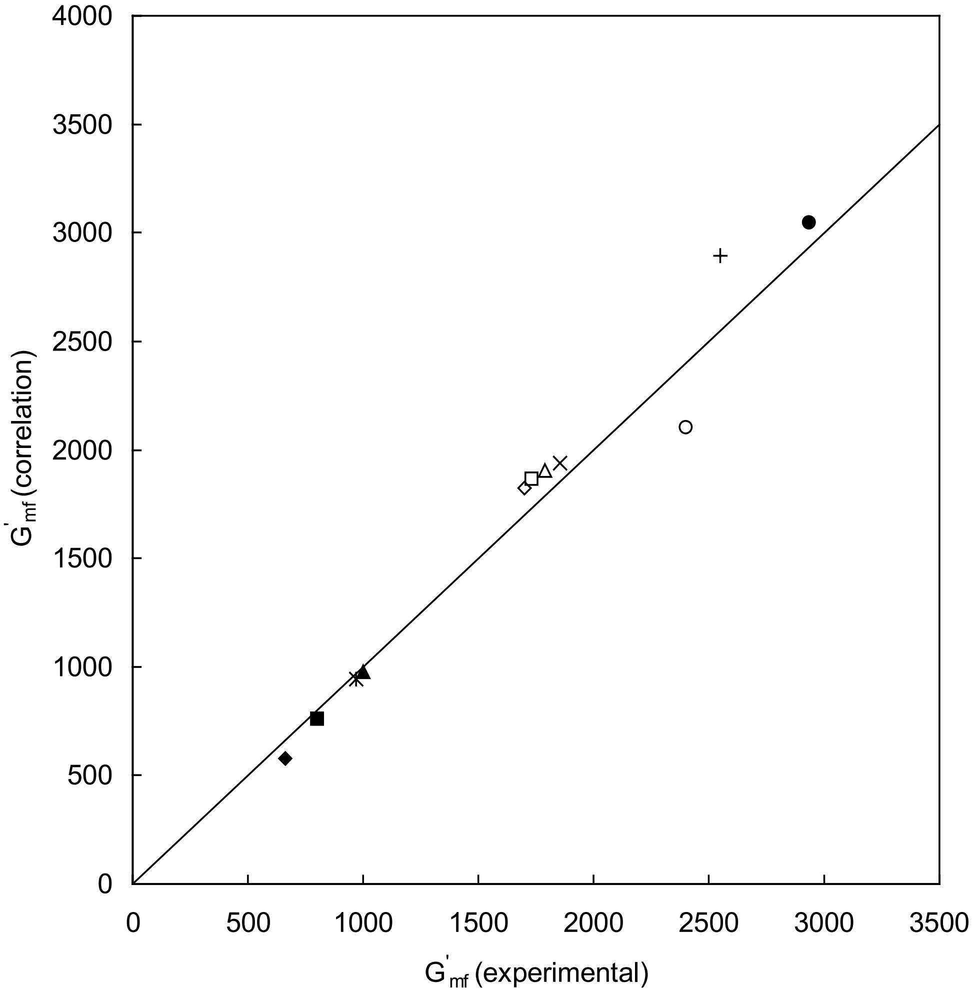


**Fig. 7.6** Comparison between experimental and predicted values of minimum fluidizing mass velocity for bed with rod promoter

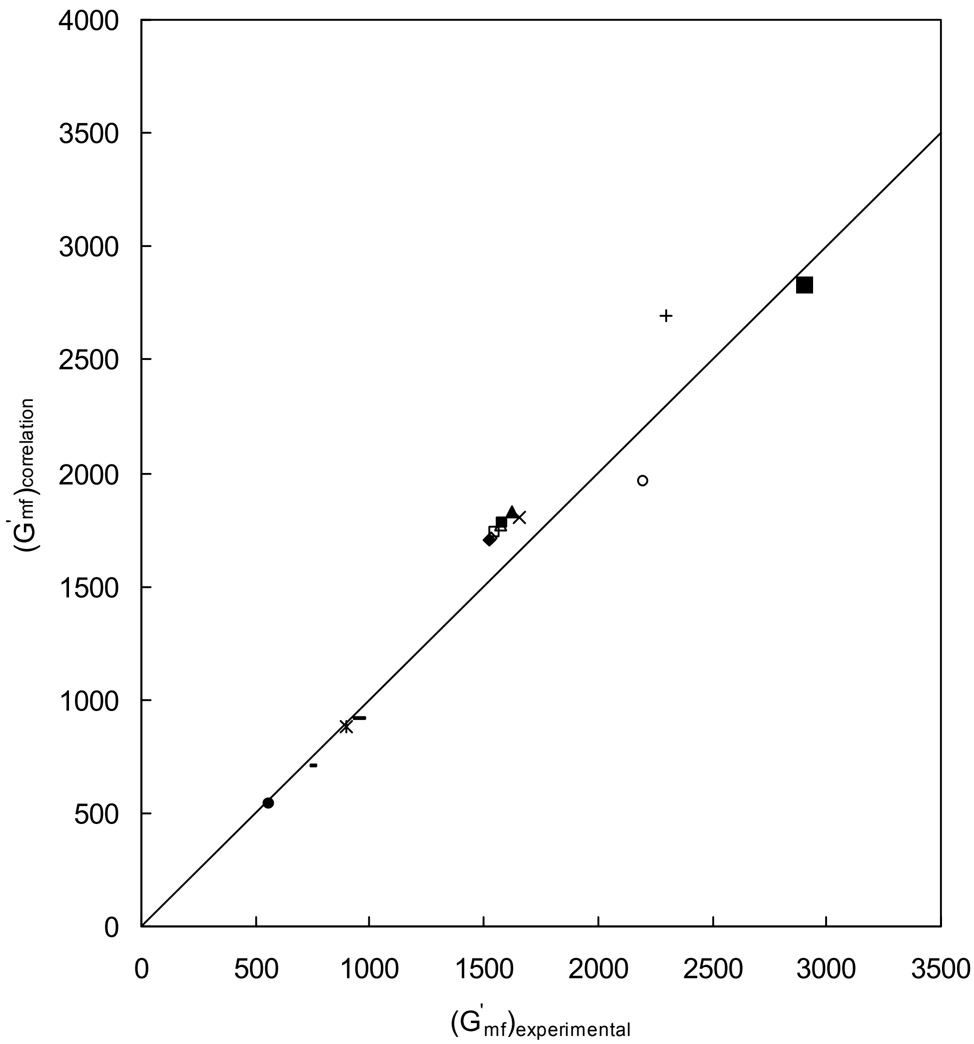


**Fig. 7.7** Comparison between experimental and calculated values of minimum fluidizing mass velocity for bed with disk promoter

# CHAPTER VIII

# Bubble behaviour

## 8.1 Introduction

Fluidized beds of fine powder exhibit some particulate behaviour above the minimum fluidization velocity. For these systems, it is possible to obtain homogeneous expansion without bubbles. The upper velocity limit for particulate state corresponds to the appearance of the first bubble and is called the minimum bubbling velocity. When the first bubble appears, the level of the upper surface of the bed sometimes falls to a value below that previously reached, thus showing a change in structure and in expansion properties. In other case, the overall bed voidage does not fall, thereby demonstrating that the emulsion phase voidage remains at a value near that reached by particulate expansion just before the first bubble appears.

A correlation for minimum bubbling velocity was suggested by Geldart [1] is,

$$U_{mb} = \mathrm{K_{mb}} \bar{d}_s \tag{8.1}$$

where $$\bar{d}_s = \frac{1}{\sum_i \left( \frac{X_i}{d_{si}} \right)} \tag{8.2}$$

and $\mathrm{K_{mb}} =$ Constant whose value is 100 in C. G. S. unit.

Abrahamsen and Geldart [2] observed that the addition of fines in a bed of small particles improves the quality of fluidization by increasing the minimum bubbling velocity and the extent of particulate expansion. They proposed the following correlation:

$$U_{mb} = 2.07 \left[ \exp\left(0.716 X_f\right) \frac{\bar{d}_s \rho_f^{0.06}}{\mu_f^{0.347}} \right] \tag{8.3}$$

where $X_f$ is the fraction of fines.

Combining minimum bubbling equation with Baeyens and Geldart's [3] equation for minimum fluidizing velocity, Geldart and Abrahamsen [2] determined the ratio-

$$\frac{U_{mb}}{U_{mf}} = \frac{2300\rho_f^{0.126}\mu_f^{0.523}\exp\left(0.716X_f\right)}{\left(\overline{d}_s\right)^{0.8} g^{0.934}\left(\rho_s - \rho_f\right)^{0.934}} \tag{8.4}$$

showing that ratio of minimum bubbling to minimum fluidization velocity increases with the increase of the fraction of fines in the bed.

It is reasonable to speculate that the large contrast in stability between gas and liquid fluidized beds is related to the presence of bubbles in most of the gas-fluidized beds, as against their absence from the liquid-fluidized ones, and hence to associate the rapid growth of instability with bubble formation. The interval between minimum bubbling velocity and minimum fluidization velocity represents the range for stable and uniform fluidization, which shrinks rapidly as the size of the particles increases [4].

Two mechanisms have been described which may limit the size of bubbles in a fluidized bed. Harrison et al. [5] suggested that large bubbles may be destroyed by particles from the wake carried up to the interior by circulating fluid. Using Davidson's model [6] of fluid circulation, they were able to estimate a maximum bubble size. The second mechanism is break-up by instability of the roof of the bubble. It is commonly observed that a large bubble is split into two smaller ones by a curtain of particles which descends from a point on its upper surface. This mechanism was suggested by Rice and Wilhelm [7].

Jackson [4] has examined the bubble stability and has concluded that large bubbles are more likely to split than the small ones and for bubbles of a given size, splitting is more likely with small particles than with large ones. This is consistent with their observation that maximum bubble size increases with increasing particle size. There is no sharply-defined maximum size, below which a bubble is stable and above which it is unstable.

Bubble size in a gas-solid fluidized bed (when size is not restricted by the column dimension) can be predicted by a correlation proposed by Rowe [8] as

$$d_b = \frac{\left(U_f - U_{mf}\right)^{1/2}\left(h + h_o\right)^{3/4}}{g^{1/4}} \tag{8.5}$$

where $(U_f - U_{mf})$ is the excess gas velocity, $h$ is the height above the distributor and $h_o$, a measure of the initial bubble size, characteristic of the distributor. $h_o$ is effectively zero for a porous plate but may be more than a meter for large tuyers.

Mori and Wen [9] have shown the effect of height from distributor plate on bubble size as

$$\frac{d_{bm} - d_b}{d_{bm} - d_{bo}} = \exp\left(\frac{-0.3h}{D_c}\right) \tag{8.6}$$

where $d_{bo} = 0.00376\left(U_f - U_{mf}\right)^2$ (8.7)

and $d_{bm} = 0.652\left[A_c\left(U_f - U_{mf}\right)\right]^{2/5}$ (8.8)

Darton et al. [10] have suggested another correlation for bubble size-

$$d_b = \frac{0.54\left(U_f - U_{mf}\right)^{0.4}\left(h + \sqrt{\frac{A_c}{n}}\right)^{0.8}}{g^{0.2}} \tag{8.9}$$

Kawabata et al. [11] have studied the effect of pressure on bubble characteristics such as the size, rising velocity and frequency in a two dimensional bed. They observed that the growth rate of bubbles depends on the properties of bed material as well as on the operating condition. It is usually smaller in a two dimensional bed than in a three-dimensional one because of frequent bubble splitting. They noted that whereas the vertical diameter remains virtually unchanged with pressure, the horizontal diameter increases. This result reveals that the bubble shape becomes flattened by pressurisation.

In the present work the bed/bubble characteristics were observed in unpromoted as well as promoted beds with rod, disk and blade promoters.

## 8.2 Experimental findings

**Unpromoted bed**

Material=Dolomite; Distributor= $D_2$; $d_p$ = 0.750 mm; $h_s$ = 12 cm;

$U_{mf}$ = 39.03 m/sec,

**At** $U_{mf}$ **:** Particle movement was initiated on the top surface of the bed.

**1.01** $U_{mf}$ ($\approx U_{mb}$)**:** Particle movement throughout the column cross section was observed.

**1.06** $U_{mf}$ **:** Localized channelling of small height was formed along the walls of the column.

**1.08** $U_{mf}$ **:** A small bubble was formed at the base and advanced slowly towards the top layer of the bed.

**1.18** $U_{mf}$ **:** A slightly larger bubble was formed at the base almost at the same point as above. At diametrically opposite location to the bubble formation point, minor channels (approximately 2 cm deep) were formed near the top layer.

**1.25** $U_{mf}$ **:** Slug was observed at about 6 cm above the distributor level.

**1.36** $U_{mf}$ **:** Slug of about 1 cm height was formed at about 5 cm above the distributor level.

**1.69** $U_{mf}$ **:** Slug of about 6 cm height was formed.

**2.00** $U_{mf}$ **:** A slug of about 15 cm height was observed.

Beyond 2.00 $U_{mf}$ : Only one slug of increasing height with increase in velocity was observed throughout the range of the experiment.

**Bed with disk promoter**

Material = Dolomite; Distributor = $D_2$ ; $d_p$ = 0.750 mm; $h_s$ = 12 cm;

$U_{mf}$ = 40.39 m/sec; Promoter = $P_6$

**At** $U_{mf}$ **:** Particle movement was initiated on the top surface of the entire bed section and little more near the column wall.

**1.02** $U_{mf}$ **:** Expansion of the bed started

**1.04** $U_{mf}$ **:** First bubble appeared

**1.11**$U_{mf}$ **:** Bubble of larger size was formed near the base.

**1.31**$U_{mf}$ **:** Slug formation at about 7 cm from distributor level was observed.

**1.43**$U_{mf}$ **:** Slug formation at about 6 cm from distributor level was observed.

**1.75**$U_{mf}$ **:** Slug was formed at about 5.5 cm from distributor level.

The slug formation was uniform and movement in the bed was smooth. The number of slugs at different levels in the fluidizer of reasonably smaller height increase with increase in flow rate. But even at higher velocity slugs were almost horizontal, uniform and their movement in the bed was smooth. There was no spouting in the bed.

**Bed with rod promoter**

Material = Dolomite; Distributor = $D_2$ ; $d_p$ = 0.750 mm; $h_s$ = 12 cm;

$U_{mf}$ = 43.24 m/sec; Promoter = $P_2$

**At** $U_{mf}$ **:** Particle movement was initiated on the top surface of the bed and throughout the section

**1.06**$U_{mf}$ **:** Locallized channel formation of about 2 cm from the top of the bed and appearance of first bubble was observed.

**1.27** $U_{mf}$ **:** A slug was formed at about 8 cm from distributor level. Formation of second slug only after breaking of the first even at higher velocity. At higher velocity, a number of slugs of comparatively smaller heights were observed simultaneously.

**1.78** $U_{mf}$ **:** Spouting was observed.

**Bed with blade promoter**

Material = Dolomite; Distributor = $D_2$; $d_p$ = 0.750 mm; $h_s$ = 12 cm; $U_{mf}$ = 42.78 m/sec;

**At** $U_{mf}$ **:** Particle movement initiated on the top of the bed

**1.01** $U_{mf}$ **:** Intense movement of the particle throughout the bed cross section with initiation of bed expansion was observed.

**1.14** $U_{mf}$ **:** First bubble appeared.

**1.27** $U_{mf}$ **:** Slug formation at about 9 cm from distributor level was observed

**1.52** $U_{mf}$ **:** Two slugs one at about 5.5 cm and another at about 10.4 cm from distributor levels were formed.

**1.93** $U_{mf}$ **:** More number of slugs with bubble of large size along the wall side were formed.

The number of slugs at different levels in the fluidizer of reasonably smaller height increased with flow rate. Even at higher velocity slugs were almost horizontal, uniform and their movement in the bed was smooth. There was no spouting in the bed. In bed with blade promoter, bubble behaviour, the nature of the slug formation and its height were more uniform and smoother than that in bed with disk promoter.

## 8.3 Results and conclusion

It has been found that the minimum bubbling velocity depends on particle diameter and the bed properties. This has been shown in Table 8.1 and Fig. 8.1. It has further been observed that for the same particle size, minimum bubbling velocity is minimum in case of unpromoted bed and maximum in the case of bed promoted with blade promoter. From Fig. 8.1, the value of $K_{mb}$ can be obtained and used to find out minimum bubbling velocity in different unpromoted and promoted beds using Eq. 8.1. The values of $K_{mb}$ has been tabulated in Table 8.2. The minimum bubbling velocity have been compared in Table 8.3 for different beds.

Bubble diameters have been calculated using Eq. 8.9 for the case of multiorifice distributor and are presented in Tables 8.4 to 8.7 respectively for unpromoted and promoted beds.

In a column generally, the upward fluid velocity is maximum at the centre of the bed and minimum near the wall. Further, according to Rowe [8] a vertical plane surface tends to displace bubbles away from it. Hence, in beds of varied geometries, the bubbles are displaced away from the wall in different magnitude and due to coalescence of bubbles in the bed, the size of bubbles are different in beds of different geometries. In this way it can be affirmed that the bed geometry which includes promoter geometry influences the minimum bubbling velocity and bubble diameter. Singh [12] also observed that the bed geometry affects the value of minimum bubbling velocity. It can be seen that in case of unpromoted bed, the periphery of column only is in contact with the fluid and give minimum peripheral contact resulting minimum bubbling velocity. In case of promoted beds, the surface of the promoter also contribute to periphery and hence more peripheral contact with the fluid. The maximum peripheral contact is in the case of bed with blade promoter followed by beds with rod and disk promoters. The maximum peripheral contact in the case of bed with blade promoter results in maximum bubbling velocity. In other words, bubble formation is delayed in the case of bed having more peripheral contact with the fluid. The delay in formation of the first bubble (viz. minimum bubbling velocity) in promoted beds may be attributed to the rearrangement bed particles which influence the voidage pattern as well as increased peripheral contact.

For identical operating conditions and equal blockage volume for the rod, disk and blade promoters, bubble diameters obtained in promoted beds have been compared with those in unpromoted ones in Table 8.8. It can be observed that the bubble diameter is maximum in case of unpromoted bed and minimum in case of bed with blade promoter. This affirms the explanation given earlier in the line of peripheral contact surface. Beds with rod and disk promoters also agree with this explanation. This may be attributed to the effectiveness of promoters in breaking the bubbles depending upon their uniqueness in shape and configuration.

Table-8.9 shows the values of minimum slugging velocity calculated with Dartons' et al. equation (Eq. 8.9) and the correlations developed [13, 14] for bed expansion and fluctuation ratio for the respective beds. It has been observed that in case of an unpromoted bed, slugging appears at a comparatively low velocity than that in a promoted bed. Among the promoted ones, the bed with a blade promoter gives the highest value for the minimum slugging velocity. This also confirms the explanation on the basis of peripheral contact surface. The values of minimum slugging velocity in case of beds with rod and disk promoters have been found almost equal which may be due to the closeness of periphery.

## Nomenclature

| | |
|---|---|
| $A_c$ | cross sectional area of column, $L^2$ |
| BP | bed with blade promoter |
| $D_c$ | column diameter, L |
| DP | bed with disk promoter |
| $d_b$ | bubble diameter, L |
| $d_{bm}$ | maximum bubble size, $0.652\left[A_c\left(U_f - U_{mf}\right)\right]^{2/5}$, L |
| $d_{bo}$ | bubble size at origin, $0.00376\left(U_f - U_{mf}\right)^2$, L |

| | |
|---|---|
| $\bar{d}_s$ | mean surface diameter, L |
| $g$ | acceleration due to gravity, $LT^{-2}$ |
| $h$ | bed height above distributor level, L |
| $h_o$ | a measure of the initial bubble size characteristic of the distributor and is effectively zero for porous plate, L |
| $h_s$ | initial static bed height, L |
| $K_{mb}$ | constant at minimum bubbling |
| $n$ | no. of orifices in distributor plate |
| RP | bed with rod promoter |
| $U_{mb}$ | minimum bubbling velocity, $LT^{-1}$ |
| $U_{mf}$ | minimum fluidization velocity, $LT^{-1}$ |
| $U_{ms}$ | minimum slugging velocity, $LT^{-1}$ |
| UP | unpromoted bed |
| $U_s$ | rise velocity of slug in a freely slugging bed, $LT^{-1}$ |
| $X_f$ | fraction of fines. |
| $X_i$ | weight fraction of particle of diameter $d_s$ |
| $\rho_f$ | dendity of fluid, $ML^{-3}$ |
| $\rho_s$ | density of solid, $ML^{-3}$ |
| $\mu_f$ | viscosity of fluid, $ML^{-1}T^{-1}$ |

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**Table 8.1** Minimum bubbling velocity

| Sl. No. | Bed Particulars | Particle diameter $d_p$ x10$^4$, m | Minimum fluidization mass velocity $G_{mf}$, kg/(hr-m$^2$) | Minimum bubbling mass velocity, $G_{mb}$, kg/(hr-m$^2$) | $\frac{G_{mb}}{G_{mf}}$ | Common parameters |
|---|---|---|---|---|---|---|
| 1 | Un-promoted bed | 11.25 | 2748 | 2781 | 1.012 | Material - dolomite, $h_s$ x10$^2$,m =12 $d_o$ x10$^3$,m =2.5 |
| 2 | | 7.25 | 1686 | 1792 | 1.063 | |
| 3 | | 4.63 | 884 | 1144 | 1.294 | |
| 4 | | 3.90 | 686 | 964 | 1.406 | |
| 5 | | 3.28 | 521 | 810 | 1.554 | |
| 6 | Bed with disk promoter | 11.25 | 2844 | 2886 | 1.015 | |
| 7 | | 7.25 | 1745 | 1860 | 1.066 | |
| 8 | | 4.63 | 914 | 1187 | 1.298 | |
| 9 | | 3.90 | 710 | 1001 | 1.409 | |
| 10 | | 3.28 | 539 | 840 | 1.559 | |
| 11 | Bed with rod promoter | 11.25 | 3046 | 3071 | 1.008 | |
| 12 | | 7.25 | 1868 | 1979 | 1.060 | |
| 13 | | 4.63 | 979 | 1263 | 1.290 | |
| 14 | | 3.90 | 761 | 1065 | 1.400 | |
| 15 | | 3.28 | 578 | 894 | 1.547 | |
| 16 | Bed with blade promoter | 11.25 | 2871 | 3194 | 1.113 | |
| 17 | | 7.25 | 1848 | 2058 | 1.114 | |
| 18 | | 4.63 | 920 | 1313 | 1.427 | |
| 19 | | 3.90 | 740 | 1107 | 1.496 | |
| 20 | | 3.28 | 562 | 930 | 1.655 | |

**Table-8.2** Values of $K_{mb}$ for different beds

| Sl. No. | Bed particulars | $K_{mb}$, M.K.S. system |
|---|---|---|
| 1 | UP | 572.31 |
| 2 | DP | 593.84 |
| 3 | RP | 631.93 |
| 4 | BP | 657.23 |

**Table 8.3** Comparison of minimum bubbling velocity ($U_{mb}$) in different beds

| Sl. No. | Bed particulars | Bed materials | Particle size $d_p$ x$10^4$,m | $U_{mf}$ x $10^2$, m/s | $U_{mb}$ x $10^2$, m/s |
|---|---|---|---|---|---|
| 1 | UP | Dolomite | 7.25 | 39.03 | 41.49 |
| 2 | DP | Dolomite | 7.25 | 40..39 | 43.05 |
| 3 | RP | Dolomite | 7.25 | 43.24 | 45.82 |
| 4 | BP | Dolomite | 7.25 | 42.78 | 47.65 |

**Table 8.4** Bubble diameter in Unpromoted bed
(Maxmimum $R$ =3.1, maximum $G_f$ =4746.1kg/hr-m$^2$,
maximum expanded bed height=37.2cm)

| Sl. No. | Fluid velocity, $U_f$ x 10$^2$, m/s | Height from distributor, $h$ x 10$^2$ , m | Bubble diameter, $D_b$ x 10$^2$ , m | Fixed parameters |
|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) |
| 1 | 48.79 | 2.0 | 1.22 | $d_p$ = 7.25x10$^{-4}$,m<br>$U_{mf}$ =0.3903 m/s<br>$U_{mb}$ =0.4149 m/s<br>$D_c$ =0.0508 m |
| 2 | 48.79 | 4.0 | 1.60 | |
| 3 | 48.79 | 6.0 | 1.96 | |
| 4 | 48.79 | 8.0 | 2.30 | |
| 5 | 48.79 | 10.0 | 2.63 | |
| 6 | 58.55 | 2.0 | 1.609 | |
| 7 | 58.55 | 4.0 | 2.11 | |
| 8 | 58.55 | 6.0 | 2.58 | |
| 9 | 58.55 | 8.0 | 3.03 | |
| 10 | 58.55 | 10.0 | 3.47 | |
| 11 | 68.30 | 2.0 | 1.89 | |
| 12 | 68.30 | 4.0 | 2.48 | |
| 13 | 68.30 | 6.0 | 3.04 | |
| 14 | 68.30 | 8.0 | 3.57 | |
| 15 | 68.30 | 10.0 | 4.08 | |
| 16 | 78.06 | 2.0 | 2.12 | |
| 17 | 78.06 | 4.0 | 2.78 | |
| 18 | 78.06 | 6.0 | 3.41 | |
| 19 | 78.06 | 8.0 | 4.00 | |
| 20 | 78.06 | 10.0 | 4.58 | |
| 21 | 87.82 | 2.0 | 2.32 | |
| 22 | 87.82 | 4.0 | 3.04 | |
| 23 | 87.82 | 6.0 | 3.73 | |
| 24 | 87.82 | 8.0 | 4.38 | |
| 25 | 87.82 | 10.0 | 5.01 | |
| 26 | 97.58 | 2.0 | 2.50 | |
| 27 | 97.58 | 4.0 | 3.28 | |
| 28 | 97.58 | 6.0 | 4.01 | |
| 29 | 97.58 | 8.0 | 4.71 | |
| 30 | 97.58 | 9.1 | 5.08 | |
| 31 | 109.28 | 2.0 | 2.69 | |
| 32 | 109.28 | 4.0 | 3.52 | |
| 33 | 109.28 | 6.0 | 4.31 | |
| 34 | 109.28 | 8.05 | 5.08 | |

**Table 8.5** Bubble diameter in bed with disk promoter
(Maximum $R$=2.16, maximum $G_f$ =5112.55 kg/hr-m$^2$,
maximum expanded bed height=25.9cm)

| Sl. No. | Fluid velocity, $U_f$ x 10$^2$, m/s | Height from distributor, $h$ x 10$^2$ , m | Bubble diameter, $D_b$ x 10$^2$ , m | Fixed parameters |
|---|---|---|---|---|
| 1 | 50.49 | 2.0 | 1.24 | $d_p$ = 7.25x10$^{-4}$,m |
| 2 | 50.49 | 4.0 | 1.62 | $U_{mf}$ =0.4039,m/s |
| 3 | 50.49 | 6.0 | 1.98 | $U_{mb}$ =0.4305,m/s |
| 4 | 50.49 | 8.0 | 2.33 | $D_c$ =0.0508 m |
| 5 | 50.49 | 10.0 | 2.67 | |
| 6 | 60.59 | 2.0 | 1.63 | |
| 7 | 60.59 | 4.0 | 2.14 | |
| 8 | 60.59 | 6.0 | 2.62 | |
| 9 | 60.59 | 8.0 | 3.08 | |
| 10 | 60.59 | 10.0 | 3.52 | |
| 11 | 70.69 | 2.0 | 1.92 | |
| 12 | 70.69 | 4.0 | 2.52 | |
| 13 | 70.69 | 6.0 | 3.08 | |
| 14 | 70.69 | 8.0 | 3.62 | |
| 15 | 70.69 | 10.0 | 4.14 | |
| 16 | 80.79 | 2.0 | 2.15 | |
| 17 | 80.79 | 4.0 | 2.82 | |
| 18 | 80.79 | 6.0 | 3.46 | |
| 19 | 80.79 | 8.0 | 4.06 | |
| 20 | 80.79 | 10.0 | 4.64 | |
| 21 | 90.89 | 2.0 | 2.35 | |
| 22 | 90.89 | 4.0 | 3.09 | |
| 23 | 90.89 | 6.0 | 3.78 | |
| 24 | 90.89 | 8.0 | 4.44 | |
| 25 | 90.89 | 9.1 | 4.79 | |
| 26 | 100.99 | 2.0 | 2.53 | |
| 27 | 100.99 | 4.0 | 3.32 | |
| 28 | 100.99 | 6.0 | 4.06 | |
| 29 | 100.99 | 8.0 | 4.77 | |
| 30 | 100.99 | 8.9 | 5.09 | |
| 31 | 111.08 | 2.0 | 2.69 | |
| 32 | 111.08 | 4.0 | 3.53 | |
| 33 | 111.08 | 6.0 | 4.32 | |
| 34 | 111.08 | 8.0 | 5.08 | |
| 35 | 117.14 | 2.0 | 2.78 | |
| 36 | 117.14 | 4.0 | 3.65 | |
| 37 | 117.14 | 6.0 | 4.47 | |
| 38 | 117.14 | 7.5 | 5.06 | |

**Table 8.6** Bubble diameter in bed with rod promoter
(Maximum, $R$ =2.18, maximum $G_f$ = 5479 kg/hr-m$^2$,
maximum expanded bed height=26.16 cm)

| Sl. No. | Fluid velocity, $U_f$ x 10$^2$, m/s | Height from distributor, $h$ x 10$^2$ , m | Bubble diameter, $D_b$ x 10$^2$ , m | Fixed parameters |
|---|---|---|---|---|
| 1 | 54.05 | 2.0 | 1.459 | $d_p$ = 7.25x10$^{-4}$,m |
| 2 | 54.05 | 4.0 | 1.90 | $U_{mf}$ =0.4324,m/s |
| 3 | 54.05 | 6.0 | 2.33 | $U_{mb}$ =0.4582,m/s |
| 4 | 54.05 | 8.0 | 2.73 | $D_c$ =0.0508 m |
| 5 | 54.05 | 10.0 | 3.13 | |
| 6 | 64.86 | 2.0 | 1.80 | |
| 7 | 64.86 | 4.0 | 2.36 | |
| 8 | 64.86 | 6.0 | 2.89 | |
| 9 | 64.86 | 8.0 | 3.40 | |
| 10 | 64.86 | 10.0 | 3.88 | |
| 12 | 75.67 | 4.0 | 2.72 | |
| 13 | 75.67 | 6.0 | 3.32 | |
| 14 | 75.67 | 8.0 | 3.90 | |
| 15 | 75.67 | 10.0 | 4.46 | |
| 16 | 86.48 | 2.0 | 2.30 | |
| 17 | 86.48 | 4.0 | 3.01 | |
| 18 | 86.48 | 6.0 | 3.69 | |
| 19 | 86.48 | 8.0 | 4.33 | |
| 20 | 86.48 | 10.0 | 4.95 | |
| 21 | 86.48 | 10.45 | 5.09 | |
| 22 | 97.29 | 2.0 | 2.49 | |
| 23 | 97.29 | 4.0 | 3.27 | |
| 24 | 97.29 | 6.0 | 4.00 | |
| 25 | 97.29 | 8.0 | 4.70 | |
| 26 | 97.29 | 9.1 | 5.07 | |
| 27 | 108.10 | 2.0 | 2.67 | |
| 28 | 108.10 | 4.0 | 3.50 | |
| 29 | 108.10 | 6.0 | 4.28 | |
| 30 | 108.10 | 8.0 | 5.03 | |
| 31 | 108.10 | 8.15 | 5.09 | |
| 32 | 118.91 | 2.0 | 2.83 | |
| 33 | 118.91 | 4.0 | 3.71 | |
| 34 | 118.91 | 6.0 | 4.54 | |
| 35 | 118.91 | 7.4 | 5.10 | |
| 36 | 125.40 | 2.0 | 2.92 | |
| 37 | 125.40 | 4.0 | 3.83 | |
| 38 | 125.40 | 6.0 | 4.68 | |
| 39 | 125.40 | 7.0 | 5.10 | |

**Table 8.7** Bubble diameter in bed with blade promoter
(Maximum $R$ =2.29; maximum $G_f$ =5479 kg/hr-m$^2$;
maximum expanded bed height=27.5cm)

| Sl. No. | Fluid velocity, $U_f$ x 10$^2$, m/s | Height from distributor, $h$ x 10$^2$ , m | Bubble diameter, $D_b$ x 10$^2$ , m | Fixed parameters |
|---|---|---|---|---|
| 1 | 54.05 | 2.0 | 1.29 | $d_p$ = 7.25x10$^{-4}$,m<br>$U_{mf}$ =0.4278,m/s<br>$U_{mb}$ =0.4765,m/s<br>$D_c$ =0.0508 m |
| 2 | 54.05 | 4.0 | 1.69 | |
| 3 | 54.05 | 6.0 | 2.07 | |
| 4 | 54.05 | 8.0 | 2.44 | |
| 5 | 54.05 | 10.0 | 2.79 | |
| 6 | 64.86 | 2.0 | 1.69 | |
| 7 | 64.86 | 4.0 | 2.22 | |
| 8 | 64.86 | 6.0 | 2.71 | |
| 9 | 64.86 | 8.0 | 3.19 | |
| 10 | 64.86 | 10.0 | 3.65 | |
| 11 | 75.67 | 2.0 | 1.98 | |
| 12 | 75.67 | 4.0 | 2.60 | |
| 13 | 75.67 | 6.0 | 3.18 | |
| 14 | 75.67 | 8.0 | 3.74 | |
| 15 | 75.67 | 10.0 | 4.28 | |
| 16 | 86.48 | 2.0 | 2.22 | |
| 17 | 86.48 | 4.0 | 2.91 | |
| 18 | 86.48 | 6.0 | 3.57 | |
| 19 | 86.48 | 8.0 | 4.19 | |
| 20 | 86.48 | 10.0 | 4.79 | |
| 21 | 97.29 | 2.0 | 2.43 | |
| 22 | 97.29 | 4.0 | 3.18 | |
| 23 | 97.29 | 6.0 | 3.90 | |
| 24 | 97.29 | 8.0 | 4.58 | |
| 25 | 97.29 | 9.1 | 4.94 | |
| 26 | 108.10 | 2.0 | 2.61 | |
| 27 | 108.10 | 4.0 | 3.42 | |
| 28 | 108.10 | 6.0 | 4.19 | |
| 29 | 108.10 | 8.0 | 4.92 | |
| 30 | 108.10 | 8.5 | 5.10 | |
| 31 | 118.91 | 2.0 | 2.77 | |
| 32 | 118.91 | 4.0 | 3.64 | |
| 33 | 118.91 | 6..0 | 4.45 | |
| 34 | 118.91 | 7.6 | 5.08 | |
| 35 | 125.40 | 2.0 | 2.87 | |
| 36 | 125.40 | 4.0 | 3.76 | |
| 37 | 125.40 | 6.0 | 4.60 | |
| 38 | 125.40 | 7.2 | 5.09 | |

**Table 8.8** Comparison of bubble diameters in different beds

| Sl. No. | Fluid velocity, $U_f$ x $10^2$,m/s | Height from distributor $h$ x $10^2$, m | $D_b$ x $10^2$, m | | | |
|---|---|---|---|---|---|---|
| | | | UP | DP | RP | BP |
| 1 | 0.6839 | 2.0 | 0.019 | 0.019 | 0.018 | 0.018 |
| 2 | 0.6839 | 4.0 | 0.025 | 0.024 | 0.023 | 0.024 |
| 3 | 0.6839 | 6.0 | 0.030 | 0.030 | 0.029 | 0.029 |
| 4 | 0.6839 | 8.0 | 0.036 | 0.035 | 0.034 | 0.034 |
| 5 | 0.6839 | 10.0 | 0.041 | 0.040 | 0.038 | 0.039 |

**Table 8.9** Comparison of minimum slugging velocity ( $U_{ms}$ ) in different beds

| Sl. No. | Bed particulars | Particle diameter $d_p$ x $10^4$, m | $U_{mb}$ x $10^2$, m/s | $U_{ms}$ x $10^2$, m/s |
|---|---|---|---|---|
| 1 | UP | 7.25 | 41.49 | 56.05 |
| 2 | DP | 7.25 | 43.05 | 60.62 |
| 3 | RP | 7.25 | 45.82 | 60.56 |
| 4 | BP | 7.25 | 47.65 | 62.66 |

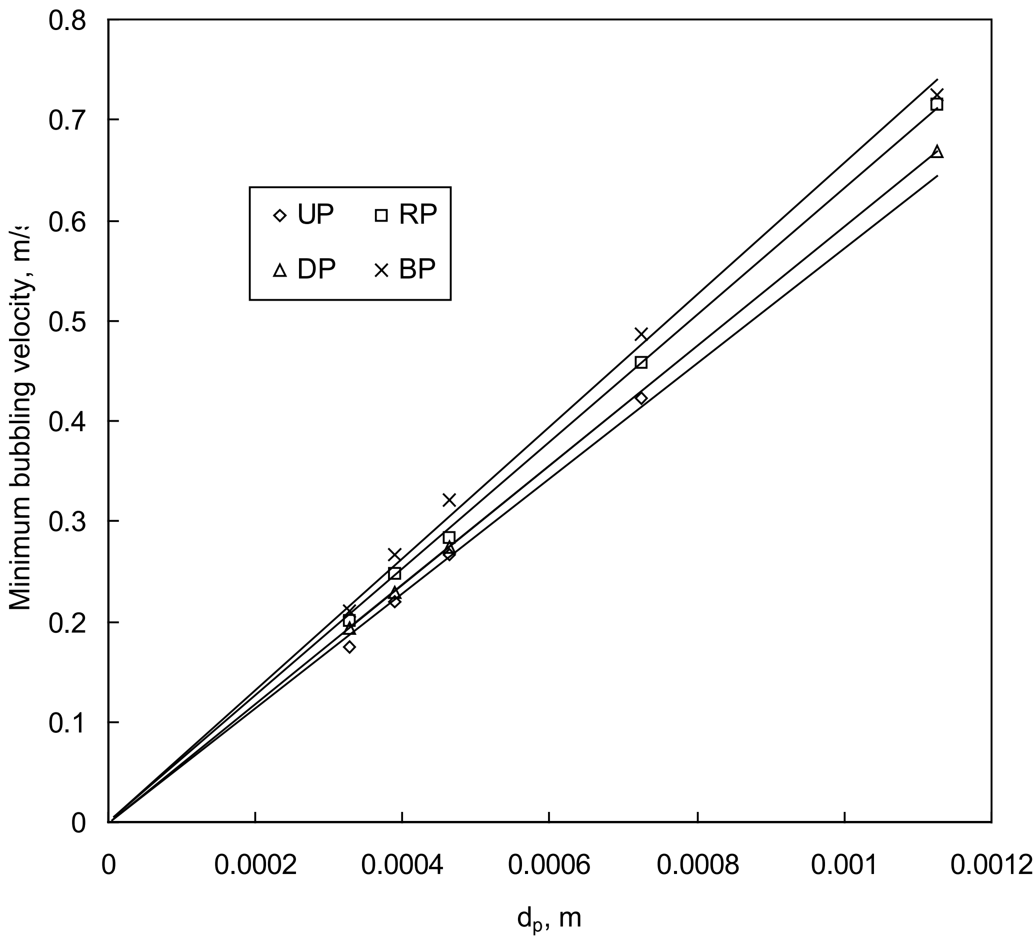


**Fig. 8.1** Variation of minimum bubbling velocity $(U_{mb})$ with particle size

# APPENDICES

## APPENDIX 1
## (Experimental data)

### Nomenclature

$M_1$- $M_4$ materials (alum, dolomite, Fe-Ore and Mn-Ore)
$D_1$- $D_5$ distributors (1.0, 1.5, 2.0, 2.5 and 3.0 mm aperture size)
$d_{p1}$- $d_{p5}$ particle sizes (0.328, 0.390, 0.463, 0.725 and 1.125 mm)
$h_{s1}$- $h_{s4}$ initial static bed heights (8, 12, 16 and 20 cm)
$P_1$- $P_4$ rod promoters (4, 8, 12, and 16 numbers of 4 mm diameter radial rods + 1 number of 6.1 mm diameter central rod)
$P_5$ - $P_8$ disk promoters (3.18, 6.36, 9.54, 12.72 mm disk thickness and 28.00 mm disk diameter)
$P_5$, $P_9$ - $P_{11}$ disk promoters (28.000, 20.260, 34.125, 39.125 mm disk diameter and 6.36 mm disk thickness)
$P_{12}$ blade promoter (38.00 mm diameter and 6.36 mm thickness)
UP unpromoted bed

Run No. 1: $M_1\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature $21.0^0C$

| Sl. No. | $G_f$, $kg.m^{-2}.hr^{-1}$ | $h_{max}$ $x10^2$, m | $h_{min}x10^2$, m | R= $h_{av}/h_s$ | r= $h_{max}/h_{min}$ | $\Delta p_d$, $N/m^2$ | $\Delta p_t$, $N/m^2$ | $\Delta p_d/\Delta p_b$ ($\Delta p_b$= $\Delta p_t$-$\Delta p_d$) |
|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 447.05 | 0.034 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 38.95 | 696.71 | 0.059 |
| 3 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 972.19 | 0.051 |
| 4 | 990.21 | 15.1 | 12.3 | 1.14 | 1.22 | 54.10 | 965.45 | 0.059 |
| 5 | 1188.26 | 17.0 | 13.0 | 1.25 | 1.31 | 62.31 | 939.92 | 0.071 |
| 6 | 1386.30 | 19.1 | 13.7 | 1.37 | 1.39 | 77.89 | 983.59 | 0.086 |
| 7 | 1584.34 | 21.7 | 14.8 | 1.52 | 1.47 | 77.89 | 994.24 | 0.085 |
| 8 | 1980.43 | 25.8 | 16.0 | 1.74 | 1.61 | 93.47 | 1009.84 | 0.102 |
| 9 | 2376.51 | 28.8 | 16.3 | 1.88 | 1.77 | 124.63 | 1027.75 | 0.138 |
| 10 | 2772.60 | 34.0 | 16.5 | 2.10 | 2.06 | 140.21 | 1056.62 | 0.153 |
| 11 | 3168.69 | 38.4 | 16.8 | 2.30 | 2.28 | 171.36 | 1139.50 | 0.177 |
| 12 | 3564.77 | 42.6 | 17.4 | 2.50 | 2.45 | 193.15 | 1178.61 | 0.196 |

Run No. 2: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 855.16 | 0.038 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1108.01 | 0.060 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1554.82 | 0.075 |
| 4 | 1980.43 | 16.8 | 13.7 | 1.27 | 1.22 | 124.63 | 1743.20 | 0.077 |
| 5 | 2178.47 | 19.5 | 14.4 | 1.41 | 1.35 | 124.63 | 1573.82 | 0.086 |
| 6 | 2376.51 | 22.1 | 15.1 | 1.55 | 1.46 | 140.21 | 1666.87 | 0.092 |
| 7 | 2574.56 | 24.5 | 15.7 | 1.67 | 1.56 | 147.99 | 1666.88 | 0.097 |
| 8 | 2772.60 | 28.0 | 17.1 | 1.88 | 1.64 | 155.78 | 1666.87 | 0.103 |
| 9 | 2970.64 | 30.1 | 17.1 | 1.96 | 1.77 | 171.36 | 1698.03 | 0.112 |
| 10 | 3168.69 | 33.0 | 17.8 | 2.12 | 1.85 | 186.94 | 1729.18 | 0.121 |
| 11 | 3564.77 | 38.1 | 18.3 | 2.35 | 2.08 | 218.10 | 1760.35 | 0.141 |
| 12 | 3960.86 | 42.3 | 19.0 | 2.55 | 2.23 | 311.57 | 2199.87 | 0.165 |

Run No. 3: $M_3\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 981.16 | 0.033 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1289.31 | 0.051 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1646.47 | 0.060 |
| 4 | 1980.43 | 13.3 | 12.8 | 1.08 | 1.04 | 155.78 | 2078.99 | 0.081 |
| 5 | 2178.47 | 17.2 | 13.8 | 1.29 | 1.25 | 171.36 | 2141.02 | 0.087 |
| 6 | 2376.51 | 20.5 | 14.8 | 1.47 | 1.39 | 178.37 | 2075.92 | 0.094 |
| 7 | 2574.56 | 22.8 | 15.0 | 1.58 | 1.52 | 186.94 | 2094.49 | 0.098 |
| 8 | 2970.64 | 28.4 | 16.8 | 1.88 | 1.69 | 218.10 | 2182.97 | 0.111 |
| 9 | 3168.69 | 29.7 | 16.8 | 1.94 | 1.77 | 233.67 | 2180.92 | 0.120 |
| 10 | 3366.73 | 32.3 | 17.1 | 2.06 | 1.89 | 249.25 | 2181.42 | 0.129 |
| 11 | 3564.77 | 35.7 | 16.8 | 2.19 | 2.13 | 264.83 | 2183.89 | 0.138 |
| 12 | 3960.86 | 38.2 | 17.3 | 2.31 | 2.21 | 311.57 | 2321.70 | 0.155 |
| 13 | 4013.20 | 40.9 | 17.9 | 2.45 | 2.28 | 373.88 | 2710.63 | 0.160 |
| 14 | 4379.65 | 48.1 | 18.5 | 2.78 | 2.60 | 436.19 | 2900.54 | 0.177 |
| 15 | 4746.10 | 50.8 | 18.5 | 2.89 | 2.75 | 560.82 | 3407.62 | 0.197 |

Run No. 4: $M_4\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature 19.5$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12 | 12.0 | 1.00 | 1.00 | 46.74 | 946.74 | 0.052 |
| 2 | 1188.26 | 12 | 12.0 | 1.00 | 1.00 | 109.05 | 1530.05 | 0.077 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 171.36 | 1853.82 | 0.102 |
| 4 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 2196.53 | 0.093 |
| 5 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 2430.22 | 0.091 |
| 6 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2586.00 | 0.092 |
| 7 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2726.21 | 0.087 |
| 8 | 2574.56 | 12.0 | 12.0 | 1.00 | 1.00 | 233.67 | 2819.66 | 0.090 |
| 9 | 2772.60 | 15.1 | 13.0 | 1.17 | 1.16 | 249.25 | 2819.66 | 0.097 |
| 10 | 2970.64 | 18.0 | 14.0 | 1.33 | 1.29 | 264.83 | 2819.67 | 0.104 |
| 11 | 3168.69 | 22.3 | 14.5 | 1.53 | 1.54 | 280.41 | 2876.80 | 0.108 |
| 12 | 3564.77 | 28.5 | 15.6 | 1.84 | 1.82 | 295.99 | 2850.82 | 0.116 |
| 13 | 3762.813 | 31.7 | 15.7 | 1.97 | 2.02 | 311.57 | 2881.98 | 0.121 |
| 14 | 3960.86 | 33.8 | 15.9 | 2.07 | 2.12 | 311.57 | 2897.56 | 0.121 |
| 15 | 4013.20 | 36.0 | 16.0 | 2.16 | 2.25 | 327.14 | 2944.30 | 0.125 |
| 16 | 4379.65 | 40.3 | 16.8 | 2.38 | 2.40 | 389.46 | 3006.61 | 0.149 |

Run No. 5: $M_2\backslash D_1\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature 20.0$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 545.24 | 1215.11 | 0.814 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 887.96 | 1651.30 | 1.163 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 1168.37 | 2274.43 | 1.056 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 1557.83 | 2741.78 | 1.316 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 1962.86 | 3520.69 | 1.260 |
| 6 | 1782.39 | 13.2 | 12.5 | 1.07 | 1.06 | 2445.79 | 3863.41 | 1.725 |
| 7 | 1980.43 | 15.1 | 13.3 | 1.18 | 1.14 | 2913.14 | 4486.55 | 1.852 |
| 8 | 2178.47 | 17.0 | 13.9 | 1.29 | 1.22 | 3473.96 | 5047.36 | 2.208 |
| 9 | 2376.51 | 18.9 | 14.3 | 1.38 | 1.32 | 4050.35 | 5763.96 | 2.364 |
| 10 | 2574.56 | 21.0 | 14.7 | 1.49 | 1.43 | 4813.69 | 6355.94 | 3.121 |
| 11 | 2772.60 | 22.9 | 14.8 | 1.57 | 1.55 | 5561.45 | 7166.01 | 3.466 |
| 12 | 2970.64 | 24.4 | 15.0 | 1.64 | 1.63 | 6371.52 | 7789.14 | 4.495 |
| 13 | 3168.69 | 26.7 | 15.8 | 1.77 | 1.69 | 6994.65 | 8723.84 | 4.045 |

Run No. 6: $M_2\backslash D_2\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 716.60 | 0.15 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1199.53 | 0.185 |
| 3 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 249.25 | 1479.94 | 0.203 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 327.14 | 1682.45 | 0.241 |
| 5 | 1782.39 | 13.4 | 12.5 | 1.08 | 1.07 | 405.04 | 1499.74 | 0.370 |
| 6 | 1980.43 | 16.0 | 13.2 | 1.22 | 1.21 | 467.35 | 1650.51 | 0.395 |
| 7 | 2178.47 | 18.1 | 14.1 | 1.34 | 1.28 | 545.24 | 1784.42 | 0.440 |
| 8 | 2376.51 | 20.1 | 14.7 | 1.45 | 1.37 | 623.13 | 1894.82 | 0.490 |
| 9 | 2574.56 | 22.7 | 15.5 | 1.59 | 1.46 | 716.60 | 2068.68 | 0.530 |
| 10 | 2772.60 | 24.5 | 15.4 | 1.66 | 1.59 | 825.65 | 2201.73 | 0.600 |
| 11 | 3168.69 | 28.6 | 16.1 | 1.86 | 1.78 | 1074.90 | 2461.37 | 0.775 |
| 12 | 3366.73 | 31.3 | 17.2 | 2.02 | 1.82 | 1246.26 | 2554.84 | 0.952 |
| 13 | 3564.77 | 33.3 | 17.1 | 2.10 | 1.95 | 1402.05 | 2648.31 | 1.125 |
| 14 | 3762.81 | 35.9 | 18.0 | 2.25 | 1.99 | 1370.89 | 2804.09 | 0.957 |
| 15 | 3960.86 | 38.6 | 18.7 | 2.39 | 2.06 | 1666.88 | 2866.40 | 1.390 |
| 16 | 4013.20 | 39.9 | 18.9 | 2.45 | 2.11 | 2025.18 | 3471.74 | 1.400 |
| 17 | 4379.65 | 43.2 | 19.2 | 2.60 | 2.25 | 2554.84 | 4224.67 | 1.530 |

Run No. 7: $M_2\backslash D_3\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 311.56 | 0.053 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 529.66 | 0.063 |
| 3 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 685.45 | 0.100 |
| 4 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 934.69 | 0.111 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 140.21 | 1402.04 | 0.111 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1557.83 | 0.111 |
| 7 | 1782.39 | 13.5 | 12.6 | 1.09 | 1.07 | 171.36 | 1542.24 | 0.125 |
| 8 | 1980.43 | 17.0 | 14.2 | 1.30 | 1.20 | 186.94 | 1541.58 | 0.138 |
| 9 | 2178.47 | 19.0 | 14.1 | 1.38 | 1.35 | 218.10 | 1652.97 | 0.152 |
| 10 | 2376.51 | 21.1 | 14.9 | 1.50 | 1.42 | 249.25 | 1713.61 | 0.170 |
| 11 | 2772.60 | 24.7 | 15.6 | 1.68 | 1.58 | 311.57 | 1807.08 | 0.208 |
| 12 | 2970.64 | 27.7 | 16.3 | 1.83 | 1.70 | 373.88 | 1838.24 | 0.255 |
| 13 | 3168.69 | 29.8 | 16.5 | 1.93 | 1.81 | 436.19 | 1869.39 | 0.304 |
| 14 | 3366.73 | 32.1 | 17.1 | 2.05 | 1.88 | 482.93 | 1931.71 | 0.333 |
| 15 | 3564.77 | 33.8 | 17.1 | 2.12 | 1.97 | 529.66 | 1931.71 | 0.378 |
| 16 | 3762.81 | 36.9 | 18.4 | 2.30 | 2.01 | 591.97 | 1994.02 | 0.422 |
| 17 | 4013.20 | 40.3 | 18.7 | 2.46 | 2.15 | 810.07 | 2610.23 | 0.450 |
| 18 | 4379.65 | 46.2 | 19.8 | 2.75 | 2.34 | 965.85 | 2788.21 | 0.530 |

Run No. 8: $M_2\backslash D_5\backslash d_{p4}\backslash h_{s2}\backslash UP$ Temperature 21.0$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 50.63 | 870.63 | 0.062 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1026.52 | 0.056 |
| 3 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1104.52 | 0.052 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 58.42 | 1308.42 | 0.047 |
| 5 | 1782.39 | 14.0 | 12.8 | 1.12 | 1.09 | 62.31 | 1717.78 | 0.038 |
| 6 | 1980.43 | 17.1 | 13.8 | 1.29 | 1.24 | 62.31 | 1752.26 | 0.037 |
| 7 | 2178.47 | 20.5 | 14.2 | 1.44 | 1.45 | 66.21 | 1808.52 | 0.038 |
| 8 | 2376.51 | 23.5 | 14.8 | 1.59 | 1.58 | 77.89 | 1861.45 | 0.044 |
| 9 | 2574.56 | 26.4 | 16.1 | 1.77 | 1.64 | 79.45 | 1868.68 | 0.044 |
| 10 | 2772.60 | 29.3 | 16.7 | 1.92 | 1.75 | 85.68 | 1887.85 | 0.048 |
| 11 | 2970.64 | 32.5 | 17.4 | 2.08 | 1.87 | 97.36 | 1920.81 | 0.053 |
| 12 | 3168.69 | 35.3 | 17.3 | 2.19 | 2.04 | 109.05 | 1956.99 | 0.059 |
| 13 | 3366.73 | 38.3 | 18.1 | 2.35 | 2.11 | 109.05 | 1985.78 | 0.058 |
| 14 | 3564.77 | 40.9 | 17.6 | 2.44 | 2.32 | 112.94 | 2015.99 | 0.059 |
| 15 | 3960.86 | 46.7 | 19.4 | 2.75 | 2.41 | 128.52 | 2062.10 | 0.066 |
| 16 | 4013.20 | 48.1 | 19.4 | 2.81 | 2.48 | 140.20 | 2230.16 | 0.067 |
| 17 | 4379.65 | 51.5 | 19.8 | 2.97 | 2.60 | 179.15 | 2302.69 | 0.084 |

Run No. 9: $M_2\backslash D_4\backslash d_{p1}\backslash h_{s2}\backslash UP$ Temperature 19.5$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 46.73 | 801.73 | 0.062 |
| 2 | 475.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1127.89 | 0.074 |
| 3 | 594.13 | 12.5 | 12.2 | 1.03 | 1.02 | 93.47 | 2318.95 | 0.042 |
| 4 | 673.35 | 13.7 | 12.7 | 1.10 | 1.08 | 93.47 | 2125.43 | 0.046 |
| 5 | 792.17 | 15.9 | 13.4 | 1.22 | 1.18 | 93.47 | 1890.97 | 0.052 |
| 8 | 990.21 | 18.1 | 14.7 | 1.37 | 1.23 | 93.47 | 1705.02 | 0.058 |
| 9 | 1188.25 | 19.4 | 14.5 | 1.41 | 1.34 | 93.47 | 1488.55 | 0.067 |
| 10 | 1386.30 | 22.4 | 15.2 | 1.57 | 1.47 | 109.05 | 1525.28 | 0.077 |
| 11 | 1584.34 | 26.0 | 16.0 | 1.75 | 1.62 | 109.05 | 1320.72 | 0.090 |
| 12 | 1980.43 | 31.3 | 16.2 | 1.98 | 1.93 | 140.21 | 1359.43 | 0.115 |
| 13 | 2376.51 | 35.8 | 17.3 | 2.21 | 2.07 | 171.36 | 1353.15 | 0.145 |
| 14 | 2772.60 | 40.4 | 17.0 | 2.39 | 2.38 | 186.94 | 1340.89 | 0.162 |
| 15 | 3168.69 | 46.0 | 17.6 | 2.65 | 2.61 | 202.52 | 1321.42 | 0.181 |
| 16 | 3564.77 | 50.5 | 18.8 | 2.89 | 2.68 | 264.83 | 1622.93 | 0.195 |

Run No. 10: $M_2\backslash D_4\backslash d_{p2}\backslash h_{s2}\backslash UP$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1012.59 | 0.066 |
| 2 | 712.95 | 12.5 | 12.2 | 1.03 | 1.02 | 77.89 | 1246.26 | 0.067 |
| 3 | 792.17 | 14.0 | 12.8 | 1.12 | 1.09 | 93.47 | 2082.19 | 0.047 |
| 4 | 871.39 | 15.2 | 13.2 | 1.18 | 1.15 | 93.47 | 1926.22 | 0.051 |
| 5 | 990.21 | 16.9 | 13.7 | 1.28 | 1.23 | 109.05 | 2091.78 | 0.055 |
| 6 | 1188.26 | 18.0 | 14.0 | 1.32 | 1.29 | 109.05 | 1840.00 | 0.063 |
| 7 | 1386.30 | 20.2 | 14.6 | 1.45 | 1.38 | 109.05 | 1736.66 | 0.067 |
| 8 | 1584.34 | 23.2 | 14.9 | 1.59 | 1.56 | 124.63 | 1702.23 | 0.079 |
| 9 | 1980.43 | 28.9 | 16.1 | 1.88 | 1.79 | 140.21 | 1526.67 | 0.101 |
| 10 | 2376.51 | 34.9 | 16.5 | 2.14 | 2.11 | 155.78 | 1487.23 | 0.117 |
| 11 | 3168.69 | 43.5 | 17.0 | 2.52 | 2.56 | 218.10 | 1593.10 | 0.158 |
| 12 | 3564.77 | 50.3 | 17.8 | 2.84 | 2.82 | 311.57 | 1711.57 | 0.223 |
| 13 | 3960.86 | 51.8 | 18.1 | 2.91 | 2.87 | 358.30 | 1858.30 | 0.239 |

Run No. 11: $M_2\backslash D_4\backslash d_{p3}\backslash h_{s2}\backslash UP$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 560.82 | 0.059 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 887.96 | 0.096 |
| 3 | 712.95 | 12.0 | 12.0 | 1.00 | 1.00 | 84.12 | 1028.16 | 0.089 |
| 4 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.45 | 1168.37 | 0.087 |
| 5 | 871.39 | 12.0 | 12.0 | 1.00 | 1.00 | 102.82 | 1339.74 | 0.083 |
| 6 | 1188.26 | 16.7 | 13.6 | 1.26 | 1.23 | 109.05 | 1957.36 | 0.059 |
| 7 | 1386.30 | 19.1 | 14.5 | 1.40 | 1.32 | 109.05 | 1840.00 | 0.063 |
| 8 | 1584.34 | 21.3 | 14.9 | 1.51 | 1.43 | 109.05 | 1689.49 | 0.069 |
| 9 | 1782.39 | 24.3 | 15.4 | 1.65 | 1.58 | 124.63 | 1608.32 | 0.084 |
| 10 | 1980.43 | 27.6 | 16.5 | 1.84 | 1.67 | 124.63 | 1573.41 | 0.086 |
| 11 | 2376.51 | 33.8 | 17.9 | 2.15 | 1.89 | 155.78 | 1651.29 | 0.104 |
| 12 | 2772.60 | 37.8 | 17.0 | 2.28 | 2.22 | 171.36 | 1553.30 | 0.124 |
| 13 | 3168.69 | 44.1 | 17.6 | 2.57 | 2.50 | 202.52 | 1638.83 | 0.141 |
| 14 | 3564.77 | 48.3 | 18.0 | 2.76 | 2.69 | 264.83 | 1899.58 | 0.162 |

Run No. 12: $M_2\backslash D_4\backslash d_{p5}\backslash h_{s2}\backslash UP$ Temperature $19.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 342.72 | 0.100 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 46.73 | 626.59 | 0.081 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 953.38 | 0.089 |
| 4 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 124.63 | 1201.01 | 0.116 |
| 5 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1751.81 | 0.119 |
| 6 | 2574.56 | 12.0 | 12.0 | 1.00 | 1.00 | 193.17 | 1835.75 | 0.118 |
| 7 | 2772.60 | 12.7 | 12.3 | 1.04 | 1.03 | 202.52 | 2220.10 | 0.100 |
| 8 | 2970.64 | 16.2 | 13.6 | 1.24 | 1.19 | 218.10 | 2383.59 | 0.101 |
| 9 | 3168.69 | 19.3 | 14.4 | 1.40 | 1.34 | 249.25 | 2514.59 | 0.110 |
| 10 | 3366.73 | 22.0 | 15.2 | 1.55 | 1.45 | 280.41 | 2567.26 | 0.123 |
| 11 | 3564.77 | 23.1 | 15.6 | 1.61 | 1.48 | 295.99 | 2597.31 | 0.129 |
| 12 | 3762.81 | 26.2 | 16.0 | 1.76 | 1.64 | 311.57 | 2689.51 | 0.131 |
| 13 | 3960.86 | 29.0 | 17.1 | 1.92 | 1.69 | 342.72 | 2839.13 | 0.137 |
| 14 | 4379.65 | 36.2 | 17.7 | 2.25 | 2.04 | 402.55 | 2980.03 | 0.156 |

Run No. 13: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s1}\backslash UP$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 8.0 | 8.0 | 1.00 | 1.00 | 46.73 | 389.46 | 0.136 |
| 2 | 1188.26 | 8.0 | 8.0 | 1.00 | 1.00 | 77.89 | 638.71 | 0.139 |
| 3 | 1584.34 | 8.0 | 8.0 | 1.00 | 1.00 | 124.63 | 974.63 | 0.160 |
| 4 | 1980.43 | 11.2 | 9.1 | 1.27 | 1.23 | 124.63 | 1098.30 | 0.128 |
| 5 | 2178.47 | 13.5 | 9.8 | 1.45 | 1.38 | 130.86 | 1095.92 | 0.136 |
| 6 | 2376.51 | 15.5 | 10.4 | 1.62 | 1.49 | 140.21 | 1059.33 | 0.153 |
| 7 | 2574.56 | 17.1 | 10.6 | 1.73 | 1.61 | 149.55 | 1101.98 | 0.157 |
| 8 | 2772.60 | 20.0 | 11.5 | 1.97 | 1.74 | 155.78 | 1106.06 | 0.164 |
| 9 | 2970.64 | 22.5 | 11.8 | 2.14 | 1.91 | 171.36 | 1106.06 | 0.183 |
| 10 | 3168.69 | 25.5 | 12.9 | 2.40 | 1.98 | 186.94 | 1121.64 | 0.200 |
| 11 | 3366.73 | 27.8 | 13.4 | 2.57 | 2.08 | 218.10 | 1224.70 | 0.217 |
| 12 | 3564.77 | 28.9 | 13.5 | 2.65 | 2.14 | 249.25 | 1335.25 | 0.230 |
| 13 | 3762.81 | 30.8 | 13.6 | 2.77 | 2.27 | 264.83 | 1382.26 | 0.237 |
| 14 | 3960.86 | 35.2 | 14.7 | 3.12 | 2.39 | 280.41 | 1358.91 | 0.260 |
| 15 | 4013.20 | 36.1 | 14.6 | 3.17 | 2.47 | 358.30 | 1637.94 | 0.280 |
| 16 | 4379.65 | 39.0 | 15.1 | 3.38 | 2.59 | 451.77 | 1863.55 | 0.320 |

Run No. 14: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s3}\backslash UP$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 16.0 | 16.0 | 1.00 | 1.00 | 46.73 | 887.97 | 0.056 |
| 2 | 1188.26 | 16.0 | 16.0 | 1.00 | 1.00 | 85.68 | 1370.89 | 0.067 |
| 3 | 1584.34 | 16.0 | 16.0 | 1.00 | 1.00 | 109.05 | 1947.29 | 0.059 |
| 4 | 1782.39 | 17.8 | 16.8 | 1.08 | 1.06 | 124.63 | 2568.36 | 0.051 |
| 5 | 1980.43 | 21.1 | 17.9 | 1.22 | 1.18 | 140.21 | 2557.62 | 0.058 |
| 6 | 2178.47 | 24.1 | 18.4 | 1.33 | 1.31 | 140.21 | 2436.06 | 0.061 |
| 7 | 2376.51 | 27.3 | 19.8 | 1.47 | 1.38 | 140.21 | 2165.37 | 0.069 |
| 8 | 2772.60 | 35.4 | 22.6 | 1.81 | 1.57 | 171.36 | 2416.23 | 0.076 |
| 9 | 3168.69 | 41.8 | 24.1 | 2.06 | 1.73 | 186.94 | 2258.85 | 0.090 |
| 10 | 3564.77 | 47.5 | 24.1 | 2.24 | 1.97 | 233.67 | 2553.64 | 0.101 |
| 11 | 3960.86 | 54.1 | 25.5 | 2.49 | 2.12 | 264.83 | 2453.51 | 0.121 |
| 12 | 4013.2 | 54.9 | 25.5 | 2.51 | 2.16 | 273.04 | 2474.98 | 0.124 |

Run No. 15: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s4}\backslash UP$ Temperature $22.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 20.0 | 20.0 | 1.00 | 1.00 | 46.73 | 1059.32 | 0.046 |
| 2 | 1188.26 | 20.0 | 20.0 | 1.00 | 1.00 | 77.89 | 1651.30 | 0.050 |
| 3 | 1584.34 | 20.0 | 20.0 | 1.00 | 1.00 | 124.63 | 2180.96 | 0.061 |
| 4 | 1782.39 | 21.7 | 20.7 | 1.06 | 1.05 | 124.63 | 2180.96 | 0.045 |
| 5 | 1980.43 | 26.1 | 22.3 | 1.21 | 1.17 | 140.21 | 2196.54 | 0.050 |
| 6 | 2178.47 | 29.1 | 23.3 | 1.31 | 1.25 | 124.63 | 2648.32 | 0.050 |
| 7 | 2376.51 | 33.1 | 24.9 | 1.45 | 1.33 | 140.21 | 2679.42 | 0.055 |
| 8 | 2574.56 | 36.7 | 25.7 | 1.56 | 1.43 | 155.78 | 2853.32 | 0.058 |
| 9 | 2772.60 | 41.4 | 27.4 | 1.72 | 1.51 | 171.36 | 3084.56 | 0.059 |
| 10 | 3168.69 | 46.7 | 27.7 | 1.86 | 1.69 | 202.52 | 3206.56 | 0.067 |
| 11 | 3564.77 | 54.7 | 28.5 | 2.08 | 1.92 | 249.25 | 3418.23 | 0.079 |
| 12 | 3960.86 | 58.7 | 29.6 | 2.20 | 1.98 | 295.99 | 3621.72 | 0.089 |
| 13 | 4013.20 | 61.7 | 30.3 | 2.30 | 2.04 | 311.21 | 3731.10 | 0.091 |
| 14 | 4746.10 | 69.2 | 30.8 | 2.50 | 2.25 | 324.55 | 3740.87 | 0.095 |

Run No. 16: $M_1\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $19.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 342.72 | 0.048 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 38.95 | 529.66 | 0.079 |
| 3 | 673.35 | 12.0 | 12.0 | 1.00 | 1.00 | 39.50 | 607.55 | 0.070 |
| 4 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 778.91 | 0.064 |
| 5 | 871.39 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 825.65 | 0.060 |
| 6 | 990.21 | 12.5 | 12.2 | 1.03 | 1.02 | 62.31 | 825.65 | 0.082 |
| 7 | 1188.26 | 14.1 | 12.7 | 1.12 | 1.11 | 62.31 | 851.04 | 0.079 |
| 8 | 1386.30 | 14.6 | 13.0 | 1.15 | 1.12 | 77.89 | 933.82 | 0.091 |
| 9 | 1584.34 | 16.5 | 14.0 | 1.27 | 1.18 | 77.89 | 903.54 | 0.094 |
| 10 | 1782.39 | 18.1 | 14.2 | 1.35 | 1.28 | 87.24 | 887.96 | 0.109 |
| 11 | 1980.43 | 19.3 | 14.7 | 1.42 | 1.32 | 93.47 | 872.39 | 0.120 |
| 12 | 2376.51 | 21.5 | 15.0 | 1.52 | 1.44 | 124.63 | 856.80 | 0.170 |
| 13 | 2574.56 | 24.1 | 16.1 | 1.68 | 1.50 | 130.86 | 887.96 | 0.173 |
| 14 | 2772.60 | 25.5 | 16.5 | 1.75 | 1.55 | 140.21 | 934.70 | 0.176 |
| 15 | 3168.68 | 26.1 | 16.3 | 1.77 | 1.60 | 171.36 | 981.43 | 0.212 |
| 16 | 3366.73 | 28.2 | 17.1 | 1.89 | 1.65 | 202.52 | 1012.60 | 0.250 |
| 17 | 3564.77 | 29.5 | 17.7 | 1.97 | 1.67 | 249.25 | 1149.10 | 0.277 |
| 18 | 3960.86 | 30.7 | 17.8 | 2.02 | 1.72 | 280.41 | 1264.30 | 0.285 |
| 19 | 4013.20 | 32.4 | 18.4 | 2.12 | 1.76 | 290.13 | 1280.33 | 0.293 |

Run No. 17: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $21.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 747.76 | 0.044 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1152.79 | 0.057 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1588.98 | 0.074 |
| 4 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1635.72 | 0.071 |
| 5 | 1980.43 | 13.8 | 12.6 | 1.10 | 1.09 | 124.63 | 1722.45 | 0.078 |
| 6 | 2178.47 | 15.7 | 13.4 | 1.21 | 1.17 | 124.63 | 1557.83 | 0.087 |
| 7 | 2376.51 | 17.3 | 13.9 | 1.30 | 1.24 | 140.21 | 1495.51 | 0.104 |
| 8 | 2772.60 | 19.6 | 14.5 | 1.42 | 1.35 | 155.78 | 1495.51 | 0.116 |
| 9 | 3168.69 | 22.0 | 15.5 | 1.56 | 1.42 | 186.94 | 1495.51 | 0.143 |
| 10 | 3564.77 | 24.5 | 16.3 | 1.70 | 1.50 | 218.1 | 1557.83 | 0.163 |
| 11 | 3960.86 | 27.2 | 17.0 | 1.84 | 1.60 | 311.57 | 1960.09 | 0.189 |
| 12 | 4013.20 | 27.9 | 16.8 | 1.86 | 1.66 | 373.88 | 2281.43 | 0.196 |
| 13 | 4379.65 | 29.4 | 17.2 | 1.94 | 1.71 | 482.93 | 2678.07 | 0.220 |
| 14 | 4746.10 | 31.7 | 17.2 | 2.04 | 1.84 | 638.71 | 3245.69 | 0.245 |

Run No. 18: $M_3\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $19.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 1286.16 | 0.025 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1618.31 | 0.040 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1791.51 | 0.055 |
| 4 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1910.78 | 0.089 |
| 5 | 2178.47 | 13.2 | 12.5 | 1.07 | 1.06 | 171.36 | 2025.18 | 0.092 |
| 6 | 2376.51 | 15.1 | 13.2 | 1.18 | 1.14 | 178.37 | 1998.47 | 0.098 |
| 7 | 2574.56 | 17.1 | 13.8 | 1.29 | 1.24 | 186.94 | 1934.04 | 0.107 |
| 8 | 2772.60 | 18.7 | 14.4 | 1.38 | 1.30 | 202.52 | 1948.38 | 0.116 |
| 9 | 2970.64 | 19.1 | 14.8 | 1.41 | 1.29 | 218.1 | 1991.27 | 0.123 |
| 10 | 3168.69 | 20.8 | 15.2 | 1.50 | 1.37 | 233.67 | 1914.75 | 0.139 |
| 11 | 3366.73 | 22.0 | 15.5 | 1.56 | 1.42 | 249.25 | 1899.91 | 0.151 |
| 12 | 3564.77 | 23.9 | 15.9 | 1.66 | 1.50 | 264.83 | 1978.44 | 0.155 |
| 13 | 3960.86 | 25.3 | 16.0 | 1.72 | 1.58 | 311.57 | 1968.86 | 0.188 |
| 14 | 4013.20 | 26.9 | 16.8 | 1.82 | 1.60 | 373.88 | 2321.17 | 0.192 |
| 15 | 4746.10 | 29.6 | 17.4 | 1.96 | 1.70 | 560.82 | 2897.57 | 0.240 |
| 16 | 5479.00 | 33.7 | 17.6 | 2.14 | 1.91 | 623.13 | 2948.24 | 0.268 |
| 17 | 5874.77 | 35.5 | 17.3 | 2.20 | 2.05 | 657.11 | 3029.35 | 0.277 |

Run No. 19: $M_4\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 934.69 | 0.053 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1479.94 | 0.080 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 171.36 | 2056.34 | 0.091 |
| 4 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 2321.15 | 0.088 |
| 5 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 2617.15 | 0.084 |
| 6 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2772.92 | 0.085 |
| 7 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2850.82 | 0.083 |
| 8 | 2574.56 | 12.0 | 12.0 | 1.00 | 1.00 | 233.67 | 2617.16 | 0.098 |
| 9 | 2772.60 | 12.0 | 12.0 | 1.00 | 1.00 | 249.25 | 2523.68 | 0.110 |
| 10 | 2970.64 | 12.9 | 12.5 | 1.06 | 1.03 | 264.83 | 2811.27 | 0.104 |
| 11 | 3168.69 | 16.0 | 13.2 | 1.22 | 1.21 | 280.41 | 2784.07 | 0.112 |
| 12 | 3564.77 | 20.0 | 14.5 | 1.44 | 1.38 | 295.99 | 2608.41 | 0.128 |
| 13 | 3960.86 | 22.3 | 15.6 | 1.58 | 1.43 | 311.57 | 2554.84 | 0.139 |
| 14 | 4013.20 | 24.5 | 15.5 | 1.67 | 1.58 | 327.14 | 2617.15 | 0.143 |

Run No. 20: $M_2\backslash D_1\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $22.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 545.24 | 1246.26 | 0.778 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 887.97 | 1791.50 | 0.983 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 1168.37 | 2336.74 | 1.000 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 1557.83 | 2804.09 | 1.250 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 1962.86 | 3316.56 | 1.450 |
| 6 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 2445.79 | 3707.63 | 1.938 |
| 7 | 1980.43 | 13.2 | 12.5 | 1.07 | 1.05 | 2913.14 | 3949.85 | 2.810 |
| 8 | 2178.47 | 14.6 | 13.0 | 1.15 | 1.13 | 3473.96 | 4587.41 | 3.120 |
| 9 | 2376.51 | 16.0 | 13.3 | 1.22 | 1.2 | 4050.35 | 5140.83 | 3.714 |
| 10 | 2574.56 | 16.8 | 13.4 | 1.26 | 1.25 | 4813.69 | 5688.91 | 5.500 |
| 11 | 2772.60 | 18.1 | 14.3 | 1.35 | 1.27 | 5561.45 | 6458.46 | 6.200 |
| 12 | 2970.64 | 18.9 | 14.4 | 1.39 | 1.31 | 6371.52 | 7268.92 | 7.100 |
| 13 | 3168.69 | 20.4 | 14.4 | 1.45 | 1.42 | 6994.65 | 7880.05 | 7.900 |
| 14 | 3366.73 | 21.0 | 14.7 | 1.49 | 1.43 | 7835.88 | 8779.96 | 8.300 |

Run No. 21: $M_2\backslash D_2\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 872.39 | 0.120 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1215.10 | 0.147 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1479.94 | 0.145 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 327.14 | 1900.55 | 0.208 |
| 5 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 405.04 | 1900.55 | 0.271 |
| 6 | 1980.43 | 13.5 | 12.5 | 1.08 | 1.08 | 467.35 | 1366.10 | 0.520 |
| 7 | 2178.47 | 14.6 | 12.7 | 1.14 | 1.15 | 545.24 | 1485.31 | 0.580 |
| 8 | 2376.51 | 16.5 | 13.4 | 1.25 | 1.23 | 623.13 | 1567.27 | 0.660 |
| 9 | 2772.60 | 19.1 | 14.9 | 1.42 | 1.28 | 825.65 | 1857.71 | 0.800 |
| 10 | 3168.68 | 21 | 15.2 | 1.51 | 1.38 | 1074.9 | 2212.12 | 0.945 |
| 11 | 3564.77 | 22.9 | 15.5 | 1.60 | 1.48 | 1402.05 | 2617.15 | 1.154 |
| 12 | 3960.86 | 25.6 | 16.2 | 1.74 | 1.58 | 1666.88 | 2928.72 | 1.321 |
| 13 | 4013.20 | 27.9 | 17.2 | 1.88 | 1.62 | 2025.18 | 3331.75 | 1.550 |
| 14 | 4379.65 | 28.4 | 17.2 | 1.90 | 1.65 | 2554.84 | 4014.75 | 1.750 |
| 15 | 4746.10 | 30.6 | 17.4 | 2.00 | 1.76 | 3271.44 | 4829.27 | 2.100 |

Run No. 22: $M_2\backslash D_3\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.08 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 358.30 | 0.046 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 638.71 | 0.051 |
| 3 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 872.38 | 0.077 |
| 4 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1152.79 | 0.088 |
| 5 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 124.63 | 1386.46 | 0.099 |
| 6 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 140.2 | 1526.67 | 0.101 |
| 7 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1682.45 | 0.102 |
| 8 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 171.36 | 1651.29 | 0.116 |
| 9 | 1980.43 | 13.5 | 12.6 | 1.09 | 1.07 | 186.94 | 1348.06 | 0.161 |
| 10 | 2178.47 | 15.6 | 13.2 | 1.20 | 1.18 | 218.1 | 1416.45 | 0.182 |
| 11 | 2376.51 | 17.0 | 13.7 | 1.28 | 1.24 | 249.25 | 1430.53 | 0.211 |
| 12 | 2772.60 | 19.4 | 14.5 | 1.41 | 1.34 | 311.57 | 1567.90 | 0.248 |
| 13 | 3168.69 | 21.7 | 14.8 | 1.52 | 1.47 | 436.19 | 1807.08 | 0.318 |
| 14 | 3564.77 | 23.8 | 15.84 | 1.65 | 1.50 | 529.66 | 1869.39 | 0.395 |
| 15 | 3960.86 | 26.7 | 16.4 | 1.80 | 1.63 | 623.13 | 1962.86 | 0.465 |
| 16 | 4013.20 | 28.1 | 16.3 | 1.85 | 1.72 | 810.07 | 2398.44 | 0.510 |

Run No. 23: $M_2\backslash D_5\backslash d_{p4}\backslash h_{s2}\backslash P_2$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 50.63 | 829.55 | 0.065 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1222.89 | 0.047 |
| 3 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1419.18 | 0.040 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 58.42 | 1507.20 | 0.040 |
| 5 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1448.78 | 0.045 |
| 6 | 1980.43 | 13.5 | 12.6 | 1.09 | 1.07 | 62.31 | 1399.54 | 0.047 |
| 7 | 2178.47 | 15.7 | 13.3 | 1.21 | 1.18 | 66.21 | 1421.88 | 0.049 |
| 8 | 2376.51 | 18.3 | 13.9 | 1.34 | 1.32 | 77.89 | 1466.58 | 0.056 |
| 9 | 2772.60 | 21.0 | 14.6 | 1.48 | 1.44 | 85.68 | 1492.90 | 0.061 |
| 10 | 3168.69 | 23.7 | 15.7 | 1.64 | 1.51 | 109.05 | 1540.58 | 0.076 |
| 11 | 3366.73 | 25.2 | 15.8 | 1.71 | 1.59 | 109.05 | 1554.46 | 0.075 |
| 12 | 3564.77 | 26.3 | 15.9 | 1.76 | 1.65 | 112.94 | 1602.59 | 0.076 |
| 13 | 3960.86 | 27.2 | 16.0 | 1.80 | 1.70 | 128.52 | 1588.98 | 0.088 |
| 14 | 4013.20 | 28.6 | 16.3 | 1.87 | 1.75 | 140.20 | 1616.04 | 0.095 |
| 15 | 4379.65 | 31.3 | 17.6 | 2.04 | 1.78 | 179.15 | 1729.15 | 0.116 |

Run No. 24: $M_2 \backslash D_4 \backslash d_{p1} \backslash h_{s2} \backslash P_2$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 841.23 | 0.059 |
| 2 | 475.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1127.89 | 0.085 |
| 3 | 594.13 | 12.5 | 12.3 | 1.03 | 1.02 | 93.47 | 1638.47 | 0.046 |
| 4 | 673.35 | 13.7 | 12.7 | 1.10 | 1.08 | 93.47 | 1792.93 | 0.055 |
| 5 | 792.17 | 15.0 | 13.1 | 1.17 | 1.15 | 93.47 | 1488.55 | 0.067 |
| 6 | 990.21 | 15.7 | 12.6 | 1.18 | 1.24 | 93.47 | 1308.58 | 0.077 |
| 7 | 1188.26 | 17.1 | 12.9 | 1.25 | 1.33 | 93.47 | 1206.21 | 0.084 |
| 8 | 1386.30 | 19.2 | 13.5 | 1.36 | 1.42 | 109.05 | 1294.38 | 0.092 |
| 9 | 1584.34 | 21.3 | 13.5 | 1.45 | 1.57 | 109.05 | 1199.55 | 0.100 |
| 10 | 1980.43 | 22.8 | 15.2 | 1.58 | 1.50 | 140.21 | 984.85 | 0.166 |
| 11 | 2376.51 | 25.6 | 16.1 | 1.74 | 1.59 | 171.36 | 1087.70 | 0.187 |
| 12 | 2772.60 | 27.5 | 16.7 | 1.84 | 1.65 | 186.94 | 1025.20 | 0.223 |
| 13 | 3564.77 | 31.3 | 17.1 | 2.02 | 1.83 | 264.83 | 1194.10 | 0.285 |
| 14 | 3960.86 | 32.3 | 16.9 | 2.05 | 1.91 | 327.14 | 1312.50 | 0.332 |
| 15 | 4013.20 | 33.9 | 16.7 | 2.11 | 2.03 | 389.46 | 1486.50 | 0.355 |

Run No. 25: $M_2 \backslash D_4 \backslash d_{p2} \backslash h_{s2} \backslash P_2$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1094.31 | 0.065 |
| 2 | 673.35 | 12.0 | 12.0 | 1.00 | 1.00 | 75.00 | 1303.00 | 0.064 |
| 3 | 792.17 | 12.7 | 12.3 | 1.04 | 1.03 | 93.47 | 1561.47 | 0.056 |
| 4 | 871.39 | 13.7 | 12.7 | 1.10 | 1.08 | 93.47 | 1625.77 | 0.061 |
| 5 | 990.21 | 15.1 | 13.2 | 1.18 | 1.15 | 109.05 | 1563.05 | 0.075 |
| 6 | 1188.26 | 15.1 | 13.2 | 1.18 | 1.14 | 109.05 | 1438.93 | 0.082 |
| 7 | 1386.30 | 17.0 | 14.0 | 1.29 | 1.21 | 109.05 | 1334.33 | 0.089 |
| 8 | 1584.34 | 18.9 | 14.5 | 1.39 | 1.30 | 124.63 | 1386.46 | 0.099 |
| 9 | 1980.43 | 21.8 | 15.1 | 1.54 | 1.44 | 140.21 | 1402.04 | 0.111 |
| 10 | 2376.51 | 24.4 | 15.9 | 1.68 | 1.54 | 155.78 | 1448.78 | 0.141 |
| 11 | 3168.68 | 28.4 | 16.9 | 1.89 | 1.68 | 218.10 | 1443.40 | 0.178 |
| 12 | 3564.77 | 30.9 | 17.8 | 2.03 | 1.74 | 311.57 | 1543.10 | 0.253 |
| 13 | 3960.86 | 32.9 | 18.5 | 2.14 | 1.78 | 358.30 | 1615.50 | 0.285 |
| 14 | 4013.2 | 33.4 | 18.7 | 2.17 | 1.79 | 405.04 | 1686.80 | 0.316 |

Run No. 26: $M_2\backslash D_4\backslash d_{p3}\backslash h_{s2}\backslash P_2$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 467.35 | 0.071 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 981.43 | 0.086 |
| 3 | 712.95 | 12.0 | 12.0 | 1.00 | 1.00 | 84.12 | 1168.36 | 0.078 |
| 4 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1355.32 | 0.074 |
| 5 | 910.10 | 12.0 | 12.0 | 1.00 | 1.00 | 105.00 | 1448.78 | 0.078 |
| 6 | 990.21 | 12.4 | 12.3 | 1.03 | 1.01 | 109.05 | 1448.78 | 0.081 |
| 7 | 1188.26 | 14.4 | 13.0 | 1.14 | 1.11 | 109.05 | 1489.43 | 0.079 |
| 8 | 1386.30 | 15.6 | 12.8 | 1.18 | 1.22 | 109.05 | 1362.50 | 0.087 |
| 9 | 1584.34 | 17.8 | 14.3 | 1.34 | 1.24 | 109.05 | 1281.63 | 0.093 |
| 10 | 1782.39 | 18.9 | 14.3 | 1.38 | 1.32 | 124.63 | 1346.49 | 0.102 |
| 11 | 1980.43 | 21.4 | 14.9 | 1.51 | 1.44 | 124.63 | 1257.63 | 0.110 |
| 12 | 2178.47 | 22.5 | 15.2 | 1.57 | 1.48 | 140.21 | 1359.43 | 0.115 |
| 13 | 2376.51 | 23.6 | 15.3 | 1.62 | 1.54 | 155.78 | 1464.86 | 0.119 |
| 14 | 2574.56 | 25.0 | 15.8 | 1.70 | 1.58 | 165.13 | 1370.46 | 0.137 |
| 15 | 2772.60 | 26.8 | 16.4 | 1.8 | 1.63 | 171.36 | 1353.15 | 0.145 |
| 16 | 3168.69 | 28.7 | 17.4 | 1.92 | 1.65 | 202.52 | 1386.85 | 0.171 |
| 17 | 3564.77 | 30.5 | 17.7 | 2.01 | 1.72 | 264.83 | 1602.36 | 0.198 |
| 18 | 3762.81 | 31.5 | 18.2 | 2.07 | 1.73 | 295.99 | 1623.30 | 0.223 |
| 19 | 3960.86 | 32.1 | 18.0 | 2.09 | 1.78 | 327.14 | 1701.70 | 0.238 |
| 20 | 4013.20 | 34.8 | 19.4 | 2.26 | 1.79 | 389.46 | 1737.10 | 0.289 |

Run No. 27: $M_2\backslash D_4\backslash d_{p5}\backslash h_{s2}\backslash P_2$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 825.65 | 0.104 |
| 2 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 950.28 | 0.130 |
| 3 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 140.21 | 1405.58 | 0.111 |
| 4 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1515.33 | 0.141 |
| 5 | 2772.60 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 1837.17 | 0.124 |
| 6 | 2970.64 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 1773.48 | 0.140 |
| 7 | 3168.69 | 13.9 | 12.7 | 1.11 | 1.09 | 249.25 | 2122.81 | 0.133 |
| 8 | 3366.73 | 15.5 | 13.3 | 1.20 | 1.17 | 280.41 | 2166.69 | 0.149 |
| 9 | 3564.77 | 16.8 | 13.9 | 1.28 | 1.21 | 295.99 | 2199.75 | 0.155 |
| 10 | 3762.81 | 18.2 | 14.4 | 1.36 | 1.26 | 311.57 | 2223.44 | 0.163 |
| 11 | 3960.86 | 19.7 | 14.7 | 1.43 | 1.34 | 342.72 | 2321.40 | 0.173 |
| 12 | 4013.20 | 22.0 | 15.2 | 1.55 | 1.44 | 375.27 | 2396.86 | 0.186 |
| 13 | 4379.65 | 22.8 | 15.6 | 1.60 | 1.46 | 402.55 | 2456.82 | 0.196 |

Run No. 28: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s1}\backslash P_2$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 8.0 | 8.0 | 1.00 | 1.00 | 46.73 | 405.03 | 0.130 |
| 2 | 1188.26 | 8.0 | 8.0 | 1.00 | 1.00 | 77.89 | 732.18 | 0.119 |
| 3 | 1386.30 | 8.0 | 8.0 | 1.00 | 1.00 | 93.47 | 856.81 | 0.122 |
| 4 | 1584.34 | 8.0 | 8.0 | 1.00 | 1.00 | 124.63 | 856.80 | 0.170 |
| 5 | 1782.39 | 8.0 | 8.0 | 1.00 | 1.00 | 124.63 | 919.12 | 0.157 |
| 6 | 1980.43 | 9.14 | 8.46 | 1.10 | 1.08 | 124.63 | 1129.71 | 0.124 |
| 7 | 2178.47 | 11.0 | 9.05 | 1.25 | 1.21 | 130.86 | 1052.41 | 0.142 |
| 8 | 2376.51 | 12.1 | 9.36 | 1.34 | 1.29 | 140.21 | 1044.79 | 0.155 |
| 9 | 2772.60 | 14.4 | 9.64 | 1.50 | 1.49 | 155.78 | 950.28 | 0.196 |
| 10 | 2970.64 | 15.3 | 10 | 1.58 | 1.53 | 171.36 | 965.85 | 0.216 |
| 11 | 3168.69 | 16.1 | 10.2 | 1.64 | 1.58 | 186.94 | 997.01 | 0.231 |
| 12 | 3564.77 | 17.6 | 10.9 | 1.78 | 1.62 | 249.25 | 1210.62 | 0.259 |
| 13 | 3960.86 | 19.1 | 11.3 | 1.90 | 1.68 | 280.41 | 1247.34 | 0.290 |
| 14 | 4013.20 | 19.7 | 11.4 | 1.94 | 1.73 | 358.3 | 1514.11 | 0.310 |
| 15 | 4379.65 | 21.0 | 11.9 | 2.06 | 1.76 | 451.77 | 1672.77 | 0.370 |
| 16 | 4746.10 | 22.0 | 11.9 | 2.12 | 1.84 | 654.28 | 2212.1 | 0.420 |

Run No. 29: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s3}\backslash P_2$ Temperature $19.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 16.0 | 16.0 | 1.00 | 1.00 | 46.73 | 1028.16 | 0.048 |
| 2 | 1188.26 | 16.0 | 16.0 | 1.00 | 1.00 | 85.68 | 1620.15 | 0.056 |
| 3 | 1584.34 | 16.0 | 16.0 | 1.00 | 1.00 | 109.05 | 2165.39 | 0.053 |
| 4 | 1782.39 | 16.0 | 16.0 | 1.00 | 1.00 | 124.63 | 2258.85 | 0.058 |
| 5 | 1980.43 | 18.1 | 16.8 | 1.09 | 1.08 | 140.21 | 2438.74 | 0.061 |
| 6 | 2178.47 | 19.5 | 17.3 | 1.15 | 1.13 | 140.21 | 2278.34 | 0.066 |
| 7 | 2376.51 | 22.2 | 18.5 | 1.27 | 1.20 | 140.21 | 2087.49 | 0.072 |
| 8 | 2772.60 | 24.8 | 18.1 | 1.34 | 1.37 | 171.36 | 2211.36 | 0.084 |
| 9 | 3168.69 | 29.5 | 20.5 | 1.56 | 1.44 | 186.94 | 2154.73 | 0.095 |
| 10 | 3366.73 | 30.8 | 20.7 | 1.61 | 1.49 | 202.52 | 2168.73 | 0.103 |
| 11 | 3564.77 | 32.4 | 21.3 | 1.68 | 1.52 | 233.67 | 2336.66 | 0.111 |
| 12 | 3762.81 | 33.4 | 21.3 | 1.71 | 1.57 | 249.25 | 2151.92 | 0.131 |
| 13 | 3960.86 | 34.9 | 21.7 | 1.77 | 1.61 | 264.83 | 2212.11 | 0.136 |
| 14 | 4013.20 | 36.9 | 22.6 | 1.86 | 1.63 | 273.04 | 2237.36 | 0.139 |

Run No. 30: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s4}\backslash P_2$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 20.0 | 20.0 | 1.00 | 1.00 | 46.73 | 1215.10 | 0.040 |
| 2 | 1188.26 | 20.0 | 20.0 | 1.00 | 1.00 | 77.89 | 1962.84 | 0.041 |
| 3 | 1584.34 | 20.0 | 20.0 | 1.00 | 1.00 | 124.63 | 2741.75 | 0.048 |
| 4 | 1782.39 | 20.0 | 20.0 | 1.00 | 1.00 | 124.63 | 2866.40 | 0.046 |
| 5 | 1980.43 | 22.3 | 20.9 | 1.08 | 1.07 | 140.21 | 3255.99 | 0.045 |
| 6 | 2178.47 | 24.1 | 21.5 | 1.14 | 1.12 | 140.21 | 3014.43 | 0.049 |
| 7 | 2376.51 | 26.8 | 22.8 | 1.24 | 1.18 | 140.21 | 2679.46 | 0.055 |
| 8 | 2574.56 | 26.8 | 22.0 | 1.22 | 1.22 | 155.78 | 2820.51 | 0.059 |
| 9 | 2772.60 | 28.6 | 22.6 | 1.28 | 1.27 | 171.36 | 3050.25 | 0.060 |
| 10 | 3168.69 | 35.5 | 25.3 | 1.52 | 1.40 | 202.52 | 3004.05 | 0.072 |
| 11 | 3564.77 | 38.2 | 25.8 | 1.60 | 1.48 | 249.25 | 3204.59 | 0.084 |
| 12 | 3960.86 | 41.6 | 26.8 | 1.71 | 1.55 | 295.99 | 3114.94 | 0.105 |
| 13 | 4013.20 | 43.5 | 27.7 | 1.78 | 1.57 | 311.21 | 3166.3 | 0.109 |
| 14 | 4746.10 | 46.8 | 28.4 | 1.88 | 1.65 | 324.55 | 2860.1 | 0.128 |
| 15 | 5479.00 | 49.9 | 28.9 | 1.97 | 1.73 | 376.84 | 2923.00 | 0.148 |

Run No. 31: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_1$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 872.39 | 0.037 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1324.16 | 0.049 |
| 3 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1604.58 | 0.051 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1713.60 | 0.068 |
| 5 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1635.72 | 0.071 |
| 6 | 1980.43 | 13.9 | 12.8 | 1.11 | 1.09 | 124.63 | 1764.50 | 0.076 |
| 7 | 2178.47 | 16.5 | 13.8 | 1.26 | 1.20 | 124.63 | 1620.14 | 0.083 |
| 8 | 2376.51 | 17.0 | 14.0 | 1.29 | 1.22 | 140.21 | 1620.14 | 0.095 |
| 9 | 2574.56 | 19.4 | 14.7 | 1.42 | 1.32 | 147.99 | 1620.15 | 0.101 |
| 10 | 2772.60 | 22.0 | 15.0 | 1.54 | 1.47 | 155.78 | 1620.14 | 0.106 |
| 11 | 3168.69 | 24.8 | 15.7 | 1.69 | 1.58 | 186.94 | 1651.30 | 0.128 |
| 12 | 3366.73 | 26.3 | 15.9 | 1.76 | 1.65 | 202.52 | 1651.30 | 0.140 |
| 13 | 3564.77 | 27.4 | 16.1 | 1.81 | 1.70 | 218.1 | 1682.46 | 0.149 |

Run No. 32: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_3$ Temperature $20.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 810.063 | 0.040 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1370.88 | 0.048 |
| 3 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1557.82 | 0.053 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1775.92 | 0.065 |
| 5 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1713.60 | 0.068 |
| 6 | 1980.43 | 13.3 | 12.6 | 1.08 | 1.06 | 124.63 | 1620.14 | 0.083 |
| 7 | 2178.47 | 14.6 | 13.0 | 1.15 | 1.13 | 124.63 | 1436.53 | 0.095 |
| 8 | 2376.51 | 16.5 | 13.5 | 1.25 | 1.22 | 140.21 | 1414.85 | 0.110 |
| 9 | 2772.60 | 18.6 | 13.6 | 1.34 | 1.37 | 155.78 | 1392.13 | 0.126 |
| 10 | 2970.64 | 20.3 | 14.3 | 1.44 | 1.42 | 171.36 | 1459.78 | 0.133 |
| 11 | 3168.69 | 21.2 | 14.8 | 1.50 | 1.43 | 186.94 | 1458.64 | 0.147 |
| 12 | 3366.73 | 22.1 | 15.3 | 1.56 | 1.44 | 202.52 | 1460.41 | 0.161 |
| 13 | 3564.77 | 22.9 | 15.7 | 1.61 | 1.46 | 218.10 | 1478.79 | 0.173 |
| 14 | 3762.81 | 24.9 | 15.9 | 1.70 | 1.57 | 264.83 | 1713.61 | 0.188 |
| 15 | 3960.86 | 26.4 | 16.6 | 1.79 | 1.59 | 311.57 | 1744.77 | 0.203 |
| 16 | 4013.20 | 27.2 | 17.0 | 1.84 | 1.60 | 373.88 | 1775.92 | 0.210 |
| 17 | 4379.65 | 28.3 | 17.3 | 1.90 | 1.63 | 482.93 | 1869.39 | 0.232 |

Run No. 33: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_4$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 778.92 | 0.042 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 46.00 | 934.70 | 0.052 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1183.94 | 0.056 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1386.46 | 0.060 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1620.15 | 0.072 |
| 6 | 1782.385 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1495.52 | 0.079 |
| 7 | 1980.43 | 12.7 | 12.5 | 1.05 | 1.02 | 124.63 | 1620.14 | 0.083 |
| 8 | 2178.47 | 14.5 | 13.1 | 1.15 | 1.11 | 124.63 | 1370.89 | 0.100 |
| 9 | 2376.51 | 15.5 | 13.3 | 1.2 | 1.16 | 140.21 | 1402.04 | 0.111 |
| 10 | 2772.60 | 16.9 | 13.8 | 1.28 | 1.22 | 155.78 | 1354.09 | 0.130 |
| 11 | 3168.69 | 19.1 | 14.5 | 1.40 | 1.32 | 186.94 | 1433.21 | 0.150 |
| 12 | 3366.73 | 20.6 | 15.4 | 1.50 | 1.34 | 202.52 | 1422.52 | 0.166 |
| 13 | 3564.77 | 22.0 | 15.9 | 1.58 | 1.38 | 218.10 | 1436.54 | 0.179 |

Run No. 34: $M_1\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 373.88 | 0.044 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 38.95 | 560.82 | 0.075 |
| 3 | 712.95 | 12.0 | 12.0 | 1.00 | 1.00 | 40.50 | 654.29 | 0.066 |
| 4 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.75 | 763.34 | 0.065 |
| 5 | 911.00 | 12.7 | 12.3 | 1.04 | 1.03 | 46.75 | 813.14 | 0.061 |
| 6 | 990.21 | 13.6 | 12.6 | 1.09 | 1.08 | 62.31 | 978.63 | 0.068 |
| 7 | 1188.26 | 15.1 | 13.0 | 1.17 | 1.16 | 62.31 | 851.04 | 0.079 |
| 8 | 1386.30 | 18.9 | 9.9 | 1.20 | 1.19 | 77.89 | 933.82 | 0.091 |
| 9 | 1584.34 | 16.4 | 13.6 | 1.25 | 1.21 | 77.89 | 906.51 | 0.094 |
| 10 | 1782.39 | 17.0 | 13.7 | 1.28 | 1.24 | 87.24 | 977.44 | 0.098 |
| 11 | 1980.43 | 18.3 | 14.1 | 1.35 | 1.29 | 93.47 | 892.36 | 0.117 |
| 12 | 2376.51 | 20.7 | 15.3 | 1.50 | 1.35 | 124.63 | 966.73 | 0.148 |
| 13 | 2574.56 | 22.0 | 16.2 | 1.59 | 1.36 | 130.86 | 943.66 | 0.161 |
| 14 | 2772.60 | 22.5 | 16.3 | 1.62 | 1.38 | 140.21 | 979.79 | 0.167 |
| 15 | 2970.64 | 24.5 | 16.7 | 1.72 | 1.47 | 155.78 | 984.40 | 0.188 |
| 16 | 3168.69 | 25.5 | 16.7 | 1.76 | 1.53 | 171.36 | 987.36 | 0.210 |
| 17 | 3366.73 | 27.2 | 16.9 | 1.84 | 1.61 | 202.52 | 1094.68 | 0.227 |
| 18 | 3564.77 | 27.7 | 17.2 | 1.87 | 1.61 | 249.25 | 1296.52 | 0.238 |
| 19 | 3762.81 | 28.5 | 17.4 | 1.91 | 1.64 | 264.83 | 1345.77 | 0.245 |
| 20 | 3960.86 | 28.9 | 17.6 | 1.94 | 1.64 | 280.41 | 1358.91 | 0.260 |
| 21 | 4379.65 | 31.2 | 18.0 | 2.05 | 1.74 | 301.27 | 1396.80 | 0.275 |

Run No. 35: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 701.02 | 0.047 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45.00 | 919.13 | 0.052 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1106.06 | 0.060 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1355.32 | 0.061 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1448.78 | 0.081 |
| 6 | 1782.39 | 12.8 | 12.4 | 1.05 | 1.04 | 109.05 | 1635.72 | 0.071 |
| 7 | 1980.43 | 14.0 | 12.9 | 1.12 | 1.09 | 124.63 | 1644.51 | 0.082 |
| 8 | 2178.47 | 16.3 | 13.5 | 1.24 | 1.21 | 124.63 | 1557.83 | 0.087 |
| 9 | 2376.51 | 17.4 | 13.8 | 1.30 | 1.26 | 140.21 | 1573.41 | 0.098 |
| 10 | 2574.56 | 18.7 | 14.4 | 1.38 | 1.30 | 147.99 | 1573.41 | 0.104 |
| 11 | 2772.60 | 19.8 | 14.7 | 1.44 | 1.35 | 155.78 | 1573.41 | 0.110 |
| 12 | 3168.69 | 21.7 | 15.0 | 1.53 | 1.45 | 186.94 | 1604.56 | 0.132 |
| 13 | 3366.73 | 23.0 | 15.2 | 1.59 | 1.51 | 202.52 | 1635.72 | 0.141 |
| 14 | 3564.77 | 23.8 | 15.3 | 1.63 | 1.55 | 218.10 | 1651.30 | 0.152 |
| 15 | 3762.81 | 24.8 | 15.7 | 1.69 | 1.58 | 264.83 | 1831.87 | 0.169 |
| 16 | 3960.86 | 25.6 | 15.8 | 1.73 | 1.62 | 311.57 | 2071.85 | 0.177 |
| 17 | 4013.20 | 26.7 | 16.3 | 1.79 | 1.64 | 373.88 | 2394.85 | 0.185 |

Run No. 36: $M_3\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 638.71 | 0.051 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 997.01 | 0.067 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1402.04 | 0.071 |
| 4 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 124.63 | 1604.57 | 0.084 |
| 5 | 1980.43 | 12.5 | 12.2 | 1.03 | 1.02 | 155.78 | 1807.08 | 0.094 |
| 6 | 2178.47 | 14.9 | 12.9 | 1.16 | 1.15 | 171.36 | 2025.18 | 0.092 |
| 7 | 2376.51 | 15.9 | 13.4 | 1.22 | 1.19 | 178.37 | 1962.07 | 0.100 |
| 8 | 2574.56 | 17.7 | 14.0 | 1.32 | 1.26 | 186.94 | 1934.04 | 0.107 |
| 9 | 2772.6 | 19.9 | 14.9 | 1.45 | 1.33 | 202.52 | 1963.56 | 0.115 |
| 10 | 2970.64 | 21.5 | 15.0 | 1.52 | 1.44 | 218.10 | 1976.97 | 0.124 |
| 11 | 3168.69 | 22.2 | 15.0 | 1.55 | 1.48 | 233.67 | 1951.83 | 0.136 |
| 12 | 3564.77 | 23.6 | 15.5 | 1.63 | 1.52 | 264.83 | 1973.41 | 0.155 |
| 13 | 3960.86 | 25.2 | 15.8 | 1.71 | 1.59 | 311.57 | 2071.85 | 0.177 |
| 14 | 4013.2 | 26.2 | 16.3 | 1.77 | 1.61 | 373.88 | 2341.67 | 0.190 |
| 15 | 4379.65 | 27.8 | 16.6 | 1.85 | 1.68 | 436.19 | 2513.29 | 0.210 |
| 16 | 4746.10 | 29.9 | 17.4 | 1.97 | 1.72 | 560.82 | 3042.32 | 0.226 |
| 17 | 5112.55 | 32.4 | 18.2 | 2.11 | 1.78 | 623.13 | 3219.51 | 0.240 |
| 18 | 5479.00 | 33.6 | 18.5 | 2.17 | 1.82 | 623.13 | 3135.75 | 0.248 |
| 19 | 5874.77 | 35.1 | 18.9 | 2.25 | 1.86 | 657.11 | 3174.75 | 0.261 |

Run No. 37: $M_4\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 856.81 | 0.058 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1386.46 | 0.085 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 171.36 | 1947.28 | 0.097 |
| 4 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 2258.85 | 0.090 |
| 5 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 2570.43 | 0.086 |
| 6 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2788.52 | 0.085 |
| 7 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2632.74 | 0.090 |
| 8 | 2574.56 | 12.0 | 12.0 | 1.00 | 1.00 | 233.67 | 2570.42 | 0.100 |
| 9 | 2772.6 | 13.0 | 12.2 | 1.05 | 1.07 | 249.25 | 2872.93 | 0.095 |
| 10 | 3168.69 | 16.5 | 13.5 | 1.25 | 1.23 | 280.41 | 2950.98 | 0.105 |
| 11 | 3564.77 | 21.9 | 15.3 | 1.55 | 1.43 | 295.99 | 2663.89 | 0.125 |
| 12 | 3960.86 | 23.4 | 15.5 | 1.62 | 1.51 | 311.57 | 2602.53 | 0.136 |
| 13 | 4013.2 | 24.3 | 15.8 | 1.67 | 1.54 | 327.14 | 2630.94 | 0.142 |
| 14 | 4379.65 | 25.2 | 15.8 | 1.71 | 1.59 | 389.46 | 2854.40 | 0.158 |
| 15 | 4746.10 | 27.2 | 16.4 | 1.82 | 1.66 | 435.10 | 3072.05 | 0.165 |
| 16 | 5112.55 | 29.5 | 17.3 | 1.95 | 1.71 | 470.15 | 3096.71 | 0.179 |
| 17 | 5479.00 | 32.2 | 18.5 | 2.11 | 1.74 | 505.32 | 3193.17 | 0.188 |

Run No. 38: $M_2\backslash D_1\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $20.0^0C$

| | (2) | (3) | (4) | (5) | (6) | (7) | 0(8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 327.14 | 778.91 | 0.724 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 545.24 | 1277.42 | 0.745 |
| 3 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 887.96 | 1698.03 | 1.096 |
| 4 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 1168.37 | 2321.16 | 1.014 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 1557.83 | 2757.36 | 1.299 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 1962.86 | 3318.17 | 1.448 |
| 7 | 1782.39 | 12.7 | 12.3 | 1.04 | 1.03 | 2445.79 | 3572.88 | 2.170 |
| 8 | 1980.43 | 14.3 | 12.9 | 1.13 | 1.11 | 2913.14 | 4132.03 | 2.390 |
| 9 | 2178.47 | 14.6 | 13.5 | 1.17 | 1.08 | 3473.96 | 4751.38 | 2.720 |
| 10 | 2376.51 | 15.3 | 13.3 | 1.19 | 1.15 | 4050.35 | 5281.04 | 3.291 |
| 11 | 2772.60 | 16.0 | 12.8 | 1.20 | 1.25 | 5561.45 | 6854.81 | 4.300 |
| 12 | 3168.69 | 17.9 | 13.6 | 1.31 | 1.32 | 6994.65 | 8200.62 | 5.800 |
| 13 | 3564.77 | 20.1 | 14.2 | 1.43 | 1.41 | 8895.20 | 10184.36 | 6.900 |
| 14 | 3960.86 | 20.9 | 14.4 | 1.47 | 1.45 | 10764.59 | 12093.55 | 8.100 |

Run No. 39: $M_2\backslash D_2\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 638.71 | 0.079 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 810.07 | 0.130 |
| 3 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1059.32 | 0.172 |
| 4 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1246.26 | 0.177 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 249.25 | 1573.41 | 0.188 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 327.14 | 1682.45 | 0.241 |
| 7 | 1782.39 | 12.5 | 12.2 | 1.03 | 1.03 | 405.04 | 1775.92 | 0.296 |
| 8 | 1980.43 | 14.3 | 12.8 | 1.13 | 1.12 | 467.35 | 1421.13 | 0.490 |
| 9 | 2178.47 | 15.2 | 12.9 | 1.17 | 1.18 | 545.24 | 1573.99 | 0.530 |
| 10 | 2376.51 | 16.2 | 12.4 | 1.19 | 1.31 | 623.13 | 1679.28 | 0.590 |
| 11 | 2772.6 | 17.4 | 12.8 | 1.26 | 1.36 | 825.65 | 1988.54 | 0.710 |
| 12 | 3168.69 | 19.2 | 13.6 | 1.37 | 1.41 | 1074.90 | 2256.11 | 0.910 |
| 13 | 3564.77 | 21.6 | 14.9 | 1.52 | 1.45 | 1402.05 | 2631.92 | 1.140 |
| 14 | 3762.81 | 22.6 | 15.3 | 1.58 | 1.48 | 1370.89 | 2450.33 | 1.270 |
| 15 | 3960.86 | 23.0 | 15.2 | 1.59 | 1.51 | 1666.88 | 2857.51 | 1.400 |
| 16 | 4013.20 | 23.5 | 15.2 | 1.61 | 1.55 | 2025.18 | 3302.60 | 1.585 |
| 17 | 4379.65 | 26.5 | 16.2 | 1.78 | 1.63 | 2554.84 | 3863.41 | 1.952 |

Run No. 40: $M_2\backslash D_3\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 591.975 | 0.056 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 794.49 | 0.085 |
| 3 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 997.007 | 0.103 |
| 4 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 124.63 | 1246.26 | 0.111 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 140.21 | 1370.89 | 0.114 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1448.77 | 0.121 |
| 7 | 1782.39 | 12.8 | 12.4 | 1.05 | 1.04 | 171.36 | 1542.25 | 0.125 |
| 8 | 1980.43 | 14.6 | 12.8 | 1.14 | 1.14 | 186.94 | 1326.82 | 0.164 |
| 9 | 2178.47 | 16.4 | 13.3 | 1.24 | 1.23 | 218.10 | 1429.77 | 0.180 |
| 10 | 2376.51 | 17.0 | 13.2 | 1.26 | 1.29 | 249.25 | 1465.10 | 0.205 |
| 11 | 2772.6 | 19.2 | 13.9 | 1.38 | 1.38 | 311.57 | 1609.78 | 0.240 |
| 12 | 3168.69 | 20.5 | 14.1 | 1.44 | 1.45 | 436.19 | 1799.28 | 0.320 |
| 13 | 3564.77 | 22.5 | 14.8 | 1.55 | 1.52 | 529.66 | 1923.5 | 0.380 |
| 14 | 3762.81 | 23.4 | 15.3 | 1.61 | 1.53 | 591.95 | 1968.58 | 0.430 |
| 15 | 3960.86 | 24.2 | 15.4 | 1.65 | 1.57 | 623.13 | 1948.94 | 0.470 |
| 16 | 4013.20 | 25.0 | 15.5 | 1.69 | 1.61 | 810.07 | 2310.20 | 0.540 |
| 17 | 4379.65 | 27.2 | 16.3 | 1.81 | 1.67 | 965.85 | 2549.21 | 0.610 |
| 18 | 4746.10 | 28.6 | 16.7 | 1.89 | 1.71 | 1339.73 | 3281.37 | 0.690 |

Run No. 41: $M_2\backslash D_5\backslash d_{p4}\backslash h_{s2}\backslash P_6$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 50.63 | 720.423 | 0.076 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 50.63 | 1000.86 | 0.053 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1144.95 | 0.050 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1325.67 | 0.043 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 58.42 | 1351.37 | 0.045 |
| 6 | 1782.39 | 12.7 | 12.2 | 1.04 | 1.04 | 62.31 | 1746.41 | 0.037 |
| 7 | 1980.43 | 14.5 | 12.9 | 1.14 | 1.12 | 62.31 | 1518.07 | 0.043 |
| 8 | 2178.47 | 17.1 | 12.9 | 1.25 | 1.32 | 66.21 | 1537.49 | 0.045 |
| 9 | 2376.51 | 18.4 | 13.3 | 1.32 | 1.38 | 77.89 | 1589.48 | 0.052 |
| 10 | 2772.60 | 22.2 | 14.3 | 1.52 | 1.55 | 85.68 | 1622.91 | 0.056 |
| 11 | 3168.69 | 24.9 | 15.4 | 1.68 | 1.61 | 109.05 | 1623.60 | 0.072 |
| 12 | 3564.77 | 26.9 | 15.6 | 1.77 | 1.72 | 112.94 | 1650.70 | 0.073 |
| 13 | 3762.81 | 27.8 | 15.7 | 1.81 | 1.77 | 112.94 | 1682.00 | 0.072 |
| 14 | 3960.86 | 28.9 | 16.2 | 1.88 | 1.79 | 128.52 | 1715.90 | 0.081 |
| 15 | 4013.20 | 29.5 | 16.3 | 1.91 | 1.81 | 140.20 | 1733.98 | 0.088 |
| 16 | 4379.65 | 31.3 | 16.9 | 2.01 | 1.85 | 179.15 | 1858.15 | 0.107 |
| 17 | 4746.10 | 33.1 | 16.8 | 2.08 | 1.97 | 225.00 | 2008.00 | 0.126 |

Run No. 42: $M_2\backslash D_4\backslash d_{p1}\backslash h_{s2}\backslash P_6$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 946.74 | 0.056 |
| 2 | 475.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1222.89 | 0.075 |
| 3 | 554.52 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 2373.23 | 0.041 |
| 4 | 594.13 | 12.4 | 12.3 | 1.03 | 1.01 | 93.47 | 2170.58 | 0.045 |
| 5 | 712.95 | 14.5 | 12.9 | 1.14 | 1.12 | 93.47 | 1792.93 | 0.055 |
| 6 | 792.17 | 15.5 | 13.3 | 1.20 | 1.16 | 93.47 | 1705.02 | 0.058 |
| 7 | 990.21 | 16.7 | 13.6 | 1.26 | 1.23 | 93.47 | 1468.03 | 0.068 |
| 8 | 1188.26 | 19.2 | 14.1 | 1.39 | 1.36 | 93.47 | 1307.37 | 0.077 |
| 9 | 1386.30 | 19.7 | 14.1 | 1.41 | 1.40 | 109.05 | 1422.91 | 0.083 |
| 10 | 1584.34 | 21.3 | 14.7 | 1.50 | 1.45 | 109.05 | 1294.38 | 0.092 |
| 11 | 1782.39 | 22.6 | 15.1 | 1.57 | 1.50 | 124.63 | 1278.61 | 0.108 |
| 12 | 1980.43 | 23.3 | 15.1 | 1.60 | 1.55 | 140.21 | 1308.63 | 0.120 |
| 13 | 2376.51 | 24.3 | 15.3 | 1.65 | 1.59 | 171.36 | 1369.68 | 0.143 |
| 14 | 2772.6 | 28.2 | 17.1 | 1.89 | 1.65 | 186.94 | 1424.95 | 0.151 |
| 15 | 3366.73 | 29.6 | 17.2 | 1.95 | 1.72 | 233.67 | 1553.84 | 0.177 |
| 16 | 3762.81 | 30.4 | 17.2 | 1.98 | 1.77 | 295.99 | 1617.37 | 0.224 |
| 17 | 3960.86 | 31.3 | 17.4 | 2.03 | 1.80 | 327.14 | 1667.88 | 0.244 |

Run No. 43: $M_2\backslash D_4\backslash d_{p2}\backslash h_{s2}\backslash P_6$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1090.48 | 0.061 |
| 2 | 514.91 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1215.11 | 0.054 |
| 3 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1464.35 | 0.056 |
| 4 | 792.17 | 12.7 | 12.3 | 1.04 | 1.03 | 93.47 | 1792.92 | 0.055 |
| 5 | 871.39 | 13.7 | 12.7 | 1.10 | 1.08 | 93.47 | 1651.30 | 0.060 |
| 6 | 990.21 | 15.5 | 13.3 | 1.20 | 1.16 | 109.05 | 1786.74 | 0.065 |
| 7 | 1069.43 | 16.0 | 13.3 | 1.22 | 1.20 | 109.05 | 1689.48 | 0.069 |
| 8 | 1188.26 | 16.9 | 13.8 | 1.28 | 1.23 | 109.05 | 1582.70 | 0.074 |
| 9 | 1386.30 | 18.6 | 14.0 | 1.36 | 1.33 | 109.05 | 1525.28 | 0.077 |
| 10 | 1584.34 | 20.2 | 14.4 | 1.44 | 1.40 | 124.63 | 1464.36 | 0.093 |
| 11 | 1980.43 | 22.5 | 15.0 | 1.56 | 1.50 | 140.21 | 1414.85 | 0.110 |
| 12 | 2376.51 | 24.6 | 15.6 | 1.68 | 1.58 | 155.78 | 1382.39 | 0.127 |
| 13 | 3168.68 | 28.7 | 16.9 | 1.90 | 1.70 | 218.10 | 1464.39 | 0.175 |
| 14 | 3366.73 | 29.2 | 17.1 | 1.93 | 1.71 | 264.83 | 1485.24 | 0.217 |
| 15 | 3762.81 | 31.4 | 17.8 | 2.05 | 1.77 | 342.72 | 1698.03 | 0.253 |
| 16 | 3960.86 | 32.3 | 18.1 | 2.10 | 1.79 | 358.30 | 1713.61 | 0.264 |

Run No. 44: $M_2\backslash D_4\backslash d_{p3}\backslash h_{s2}\backslash P_6$ Temperature 19.0$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 591.98 | 0.056 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 872.39 | 0.098 |
| 3 | 712.95 | 12.0 | 12.0 | 1.00 | 1.00 | 84.12 | 1168.36 | 0.078 |
| 4 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1261.85 | 0.080 |
| 5 | 871.39 | 12.0 | 12.0 | 1.00 | 1.00 | 102.82 | 1386.47 | 0.080 |
| 6 | 990.21 | 12.7 | 12.3 | 1.04 | 1.03 | 109.05 | 1926.55 | 0.060 |
| 7 | 1188.26 | 15.1 | 13.1 | 1.18 | 1.15 | 109.05 | 1689.48 | 0.069 |
| 8 | 1584.34 | 18.7 | 13.7 | 1.35 | 1.36 | 109.05 | 1464.36 | 0.081 |
| 9 | 1782.39 | 20.0 | 14.3 | 1.43 | 1.40 | 124.63 | 1495.52 | 0.091 |
| 10 | 1980.43 | 21.2 | 14.6 | 1.49 | 1.45 | 124.63 | 1436.52 | 0.095 |
| 11 | 2376.51 | 23.4 | 15.2 | 1.61 | 1.54 | 155.78 | 1522.27 | 0.114 |
| 12 | 2574.56 | 24.1 | 15.5 | 1.65 | 1.56 | 165.13 | 1455.21 | 0.128 |
| 13 | 2772.60 | 25.2 | 15.6 | 1.70 | 1.61 | 171.36 | 1440.69 | 0.135 |
| 14 | 3168.69 | 27.0 | 16.2 | 1.80 | 1.67 | 202.52 | 1509.10 | 0.155 |
| 15 | 3366.73 | 28.5 | 16.6 | 1.88 | 1.71 | 218.10 | 1516.31 | 0.168 |

Run No. 45: $M_2\backslash D_4\backslash d_{p5}\backslash h_{s2}\backslash P_6$ Temperature 19.0$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 280.41 | 0.125 |
| 2 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 560.82 | 0.125 |
| 3 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 825.65 | 0.152 |
| 4 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 140.21 | 1267.95 | 0.124 |
| 5 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1444.52 | 0.149 |
| 6 | 2772.60 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 1782.00 | 0.128 |
| 7 | 2970.64 | 13.2 | 12.5 | 1.07 | 1.06 | 218.10 | 2345.37 | 0.103 |
| 8 | 3168.69 | 14.7 | 12.9 | 1.15 | 1.14 | 249.25 | 2276.38 | 0.123 |
| 9 | 3564.77 | 17.7 | 14.0 | 1.32 | 1.27 | 295.98 | 2271.01 | 0.150 |
| 10 | 3960.86 | 21.1 | 15.1 | 1.51 | 1.4 | 342.72 | 2395.26 | 0.167 |
| 11 | 4013.20 | 21.9 | 14.9 | 1.53 | 1.47 | 375.27 | 2433.10 | 0.182 |
| 12 | 4379.65 | 23.2 | 15.5 | 1.61 | 1.50 | 402.55 | 2549.21 | 0.188 |
| 13 | 4746.10 | 24.8 | 15.7 | 1.69 | 1.58 | 452.48 | 2827.85 | 0.191 |
| 14 | 5112.55 | 26.9 | 16.6 | 1.81 | 1.62 | 527.74 | 3091.01 | 0.206 |

Run No. 46: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s1}\backslash P_6$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 8.0 | 8.0 | 1.00 | 1.00 | 31.16 | 311.57 | 0.111 |
| 2 | 792.17 | 8.0 | 8.0 | 1.00 | 1.00 | 46.74 | 498.50 | 0.104 |
| 3 | 990.21 | 8.0 | 8.0 | 1.00 | 1.00 | 62.31 | 669.87 | 0.103 |
| 4 | 1188.26 | 8.0 | 8.0 | 1.00 | 1.00 | 77.89 | 856.81 | 0.100 |
| 5 | 1386.30 | 8.0 | 8.0 | 1.00 | 1.00 | 93.47 | 872.39 | 0.120 |
| 6 | 1584.34 | 8.0 | 8.0 | 1.00 | 1.00 | 124.63 | 887.96 | 0.163 |
| 7 | 1782.39 | 8.7 | 8.2 | 1.05 | 1.04 | 124.63 | 1163.21 | 0.120 |
| 8 | 1980.43 | 10.2 | 8.7 | 1.18 | 1.17 | 124.63 | 1068.80 | 0.132 |
| 9 | 2178.47 | 11.7 | 9.4 | 1.32 | 1.25 | 130.86 | 1046.00 | 0.143 |
| 10 | 2376.51 | 12.5 | 9.1 | 1.35 | 1.38 | 140.21 | 984.85 | 0.166 |
| 11 | 2574.56 | 13.3 | 9.4 | 1.42 | 1.42 | 149.55 | 1024.11 | 0.171 |
| 12 | 2772.60 | 14.4 | 9.7 | 1.51 | 1.48 | 155.78 | 1021.22 | 0.180 |
| 13 | 3168.69 | 15.7 | 10.2 | 1.62 | 1.53 | 186.94 | 1103.31 | 0.204 |
| 14 | 3366.73 | 16.2 | 10.3 | 1.66 | 1.57 | 218.10 | 1223.17 | 0.217 |
| 15 | 3564.77 | 16.9 | 10.5 | 1.71 | 1.61 | 249.25 | 1332.95 | 0.230 |
| 16 | 3762.81 | 17.8 | 10.8 | 1.79 | 1.65 | 264.83 | 1345.77 | 0.245 |
| 17 | 3960.86 | 18.3 | 11.0 | 1.83 | 1.67 | 280.41 | 1358.91 | 0.260 |
| 18 | 4013.20 | 19.2 | 11.2 | 1.90 | 1.71 | 358.3 | 1637.94 | 0.280 |
| 19 | 4379.65 | 20.4 | 11.3 | 1.98 | 1.80 | 451.77 | 1909.09 | 0.310 |
| 20 | 4746.10 | 21.5 | 11.7 | 2.07 | 1.84 | 654.29 | 2601.58 | 0.336 |

Run No. 47: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s3}\backslash P_6$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 16.0 | 16.0 | 1.00 | 1.00 | 31.16 | 763.337 | 0.043 |
| 2 | 792.17 | 16.0 | 16.0 | 1.00 | 1.00 | 46.74 | 1121.64 | 0.044 |
| 3 | 990.21 | 16.0 | 16.0 | 1.00 | 1.00 | 77.89 | 1370.88 | 0.060 |
| 4 | 1188.26 | 16.0 | 16.0 | 1.00 | 1.00 | 85.68 | 1666.87 | 0.054 |
| 5 | 1386.30 | 16.0 | 16.0 | 1.00 | 1.00 | 93.47 | 1939.50 | 0.051 |
| 6 | 1584.34 | 16.0 | 16.0 | 1.00 | 1.00 | 109.05 | 1947.29 | 0.059 |
| 7 | 1782.39 | 17.0 | 16.3 | 1.04 | 1.04 | 124.63 | 2273.42 | 0.058 |
| 8 | 1980.43 | 19.4 | 17.1 | 1.14 | 1.13 | 140.21 | 2365.77 | 0.063 |
| 9 | 2178.47 | 20.0 | 16.8 | 1.15 | 1.19 | 140.21 | 2232.9 | 0.067 |
| 10 | 2376.51 | 22.4 | 17.9 | 1.26 | 1.25 | 140.21 | 1985.08 | 0.076 |
| 11 | 2574.56 | 24.0 | 18.2 | 1.32 | 1.32 | 155.78 | 2127.68 | 0.079 |
| 12 | 2772.60 | 25.7 | 19.1 | 1.40 | 1.35 | 171.36 | 2187.36 | 0.085 |
| 13 | 3168.69 | 28.1 | 19.9 | 1.50 | 1.41 | 186.94 | 2114.16 | 0.097 |
| 14 | 3366.73 | 29.1 | 19.9 | 1.53 | 1.46 | 202.52 | 2243.27 | 0.099 |
| 15 | 3564.77 | 30.3 | 20.3 | 1.58 | 1.49 | 233.67 | 2274.42 | 0.115 |
| 16 | 3762.81 | 31.2 | 20.4 | 1.61 | 1.53 | 249.25 | 2290.01 | 0.122 |
| 17 | 3960.86 | 32.6 | 20.9 | 1.67 | 1.56 | 264.83 | 2305.58 | 0.130 |
| 18 | 4013.20 | 33.1 | 21.0 | 1.69 | 1.58 | 273.04 | 2325.97 | 0.133 |

Run No. 48: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s4}\backslash P_6$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 20.0 | 20.0 | 1.00 | 1.00 | 31.16 | 1059.34 | 0.030 |
| 2 | 792.17 | 20.0 | 20.0 | 1.00 | 1.00 | 46.74 | 1355.32 | 0.036 |
| 3 | 990.21 | 20.0 | 20.0 | 1.00 | 1.00 | 62.31 | 1822.68 | 0.035 |
| 4 | 1188.26 | 20.0 | 20.0 | 1.00 | 1.00 | 77.89 | 2258.83 | 0.036 |
| 5 | 1386.30 | 20.0 | 20.0 | 1.00 | 1.00 | 109.05 | 2414.64 | 0.047 |
| 6 | 1584.34 | 20.0 | 20.0 | 1.00 | 1.00 | 124.63 | 2445.79 | 0.054 |
| 7 | 1782.39 | 20.8 | 20.4 | 1.03 | 1.02 | 124.63 | 2913.15 | 0.045 |
| 8 | 1980.43 | 23.8 | 21.4 | 1.13 | 1.11 | 140.21 | 3123.40 | 0.047 |
| 9 | 2376.51 | 25.8 | 21.8 | 1.19 | 1.18 | 140.21 | 2663.88 | 0.056 |
| 10 | 2772.60 | 30.1 | 23.5 | 1.34 | 1.28 | 171.36 | 2757.34 | 0.066 |
| 11 | 3168.69 | 32.8 | 24.4 | 1.43 | 1.34 | 202.52 | 2819.67 | 0.077 |
| 12 | 3564.77 | 35.1 | 24.5 | 1.49 | 1.43 | 249.25 | 2913.15 | 0.094 |
| 13 | 3960.86 | 37.5 | 24.9 | 1.56 | 1.51 | 311.21 | 3041.12 | 0.114 |
| 14 | 4013.20 | 38.2 | 25.4 | 1.59 | 1.5 | 315.67 | 3013.70 | 0.117 |
| 15 | 4379.65 | 41.4 | 26.6 | 1.70 | 1.55 | 324.55 | 3051.86 | 0.119 |
| 16 | 4746.10 | 44.4 | 27.2 | 1.79 | 1.63 | 376.84 | 3210.22 | 0.133 |

Run No. 49: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_5$ Temperature $22.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 16.00 | 545.241 | 0.030 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 763.337 | 0.043 |
| 3 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45.00 | 1012.60 | 0.047 |
| 4 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1199.52 | 0.055 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1448.78 | 0.057 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1557.83 | 0.075 |
| 7 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1557.83 | 0.075 |
| 8 | 1980.43 | 13.9 | 12.7 | 1.11 | 1.09 | 124.63 | 1573.41 | 0.086 |
| 9 | 2178.47 | 15.8 | 13.2 | 1.21 | 1.20 | 124.63 | 1494.19 | 0.091 |
| 10 | 2376.51 | 18.2 | 13.9 | 1.34 | 1.31 | 140.21 | 1528.43 | 0.101 |
| 11 | 2772.60 | 21.1 | 14.7 | 1.49 | 1.44 | 155.78 | 1571.96 | 0.110 |
| 12 | 3168.69 | 23.3 | 15.1 | 1.60 | 1.54 | 186.94 | 1561.50 | 0.136 |
| 13 | 3366.73 | 24.5 | 15.5 | 1.67 | 1.58 | 202.52 | 1608.91 | 0.144 |
| 14 | 3564.77 | 25.7 | 15.8 | 1.73 | 1.62 | 218.10 | 1672.10 | 0.150 |

Run No. 50: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_7$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 16.00 | 607.56 | 0.027 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 825.65 | 0.039 |
| 3 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45.00 | 1043.73 | 0.045 |
| 4 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1293.00 | 0.051 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1417.63 | 0.058 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1448.78 | 0.081 |
| 7 | 1782.39 | 12.7 | 12.2 | 1.04 | 1.04 | 109.05 | 1511.10 | 0.078 |
| 8 | 1980.43 | 14.6 | 13.0 | 1.15 | 1.12 | 124.63 | 1626.20 | 0.083 |
| 9 | 2178.47 | 16.0 | 13.5 | 1.23 | 1.18 | 124.63 | 1557.83 | 0.087 |
| 10 | 2376.51 | 17.1 | 13.7 | 1.28 | 1.25 | 140.21 | 1573.41 | 0.098 |
| 11 | 2772.60 | 19.4 | 14.4 | 1.41 | 1.35 | 155.78 | 1604.56 | 0.108 |
| 12 | 3168.69 | 21.3 | 14.7 | 1.50 | 1.45 | 186.94 | 1613.96 | 0.131 |
| 13 | 3366.73 | 22.3 | 14.9 | 1.55 | 1.49 | 202.52 | 1638.83 | 0.141 |
| 14 | 3564.77 | 23.0 | 15.4 | 1.60 | 1.50 | 218.10 | 1691.75 | 0.148 |
| 15 | 3762.81 | 24.5 | 15.8 | 1.68 | 1.55 | 264.83 | 1841.20 | 0.168 |
| 16 | 3960.86 | 24.8 | 15.7 | 1.69 | 1.58 | 311.57 | 2061.96 | 0.178 |
| 17 | 4013.20 | 25.8 | 16.2 | 1.75 | 1.60 | 373.88 | 2331.37 | 0.191 |

Run No. 51: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_8$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 841.226 | 0.039 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45.00 | 1074.89 | 0.044 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1277.43 | 0.051 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1448.78 | 0.057 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1448.78 | 0.081 |
| 6 | 1782.39 | 12.9 | 12.3 | 1.05 | 1.05 | 109.05 | 1495.52 | 0.079 |
| 7 | 1980.43 | 14.5 | 12.9 | 1.14 | 1.12 | 124.63 | 1682.51 | 0.080 |
| 8 | 2178.47 | 15.5 | 13.6 | 1.21 | 1.14 | 124.63 | 1608.32 | 0.084 |
| 9 | 2376.51 | 16.4 | 13.6 | 1.25 | 1.21 | 140.21 | 1647.84 | 0.093 |
| 10 | 2772.6 | 18.9 | 14.4 | 1.39 | 1.31 | 155.78 | 1651.29 | 0.104 |
| 11 | 3168.69 | 20.8 | 14.7 | 1.48 | 1.42 | 186.94 | 1670.59 | 0.126 |
| 12 | 3366.73 | 21.8 | 15.0 | 1.53 | 1.45 | 202.52 | 1702.67 | 0.135 |
| 13 | 3564.77 | 22.5 | 15.2 | 1.57 | 1.48 | 218.10 | 1743.27 | 0.143 |
| 14 | 3762.81 | 23.3 | 15.5 | 1.61 | 1.51 | 264.83 | 1930.43 | 0.159 |
| 15 | 3960.86 | 24.1 | 15.7 | 1.66 | 1.53 | 311.57 | 2144.34 | 0.170 |

Run No. 52: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_9$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 810.06 | 0.040 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45.00 | 1059.31 | 0.044 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1277.43 | 0.051 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1433.21 | 0.058 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1479.94 | 0.080 |
| 6 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1557.83 | 0.075 |
| 7 | 1980.43 | 14.0 | 12.7 | 1.11 | 1.10 | 124.63 | 1604.57 | 0.084 |
| 8 | 2178.47 | 16.2 | 13.5 | 1.24 | 1.20 | 124.63 | 1663.27 | 0.081 |
| 9 | 2376.51 | 17.4 | 13.3 | 1.28 | 1.31 | 140.21 | 1733.51 | 0.088 |
| 10 | 2772.60 | 20.5 | 14.0 | 1.44 | 1.46 | 155.78 | 1666.87 | 0.103 |
| 11 | 3168.69 | 22.6 | 14.6 | 1.55 | 1.54 | 186.94 | 1744.77 | 0.120 |
| 12 | 3366.73 | 24.1 | 15.0 | 1.63 | 1.60 | 202.52 | 1775.92 | 0.129 |
| 13 | 3564.77 | 25.2 | 15.2 | 1.68 | 1.66 | 218.10 | 1838.24 | 0.135 |
| 14 | 3762.81 | 26.0 | 15.2 | 1.72 | 1.71 | 264.83 | 2066.40 | 0.147 |

Run No. 53: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_{10}$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 778.92 | 0.042 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45 | 1028.18 | 0.046 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1277.43 | 0.051 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1339.74 | 0.062 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1402.05 | 0.084 |
| 6 | 1782.39 | 13.0 | 12.5 | 1.06 | 1.04 | 109.05 | 1433.20 | 0.082 |
| 7 | 1980.43 | 14.8 | 13.0 | 1.16 | 1.14 | 124.63 | 1511.09 | 0.090 |
| 8 | 2178.47 | 15.3 | 13.3 | 1.19 | 1.15 | 124.63 | 1422.86 | 0.096 |
| 9 | 2376.51 | 16.8 | 13.7 | 1.27 | 1.22 | 140.21 | 1488.38 | 0.104 |
| 10 | 2772.60 | 18.8 | 14.3 | 1.38 | 1.31 | 155.78 | 1464.86 | 0.119 |
| 11 | 3168.69 | 21.3 | 15.1 | 1.52 | 1.41 | 186.94 | 1485.13 | 0.144 |
| 12 | 3366.73 | 22.3 | 15.4 | 1.57 | 1.45 | 202.52 | 1534.89 | 0.152 |
| 13 | 3564.77 | 22.7 | 15.4 | 1.59 | 1.47 | 218.10 | 1581.23 | 0.160 |
| 14 | 3762.81 | 23.6 | 15.8 | 1.64 | 1.49 | 264.83 | 1744.77 | 0.179 |

Run No. 54: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_{11}$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 16.00 | 503.00 | 0.033 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 686.16 | 0.048 |
| 3 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 45.00 | 845.00 | 0.056 |
| 4 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1051.31 | 0.063 |
| 5 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1177.89 | 0.071 |
| 6 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1277.05 | 0.093 |
| 7 | 1782.39 | 13.6 | 12.6 | 1.09 | 1.08 | 109.05 | 1386.46 | 0.085 |
| 8 | 1980.43 | 14.4 | 13.0 | 1.14 | 1.11 | 124.63 | 1417.62 | 0.096 |
| 9 | 2178.47 | 14.6 | 13.0 | 1.15 | 1.12 | 124.63 | 1358.59 | 0.101 |
| 10 | 2376.51 | 16.2 | 13.6 | 1.24 | 1.19 | 140.21 | 1414.85 | 0.110 |
| 11 | 2772.60 | 18.4 | 14.3 | 1.36 | 1.29 | 155.78 | 1382.39 | 0.127 |
| 12 | 3168.69 | 20.6 | 14.9 | 1.48 | 1.38 | 186.94 | 1441.57 | 0.149 |
| 13 | 3366.73 | 21.7 | 15.3 | 1.54 | 1.42 | 202.52 | 1468.27 | 0.160 |

Run No. 55: $M_1\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $22.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 38.95 | 545.24 | 0.077 |
| 2 | 712.95 | 12.0 | 12.0 | 1.00 | 1.00 | 40.50 | 638.71 | 0.068 |
| 3 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 701.023 | 0.071 |
| 4 | 990.21 | 12.6 | 12.1 | 1.03 | 1.04 | 62.31 | 1051.36 | 0.063 |
| 5 | 1069.43 | 13.8 | 12.6 | 1.10 | 1.10 | 62.31 | 992.31 | 0.067 |
| 6 | 1188.26 | 14.7 | 12.9 | 1.15 | 1.14 | 62.31 | 939.92 | 0.071 |
| 7 | 1386.30 | 15.7 | 13.6 | 1.22 | 1.15 | 77.89 | 1076.48 | 0.078 |
| 8 | 1584.34 | 16.4 | 14.0 | 1.27 | 1.17 | 77.89 | 965.85 | 0.088 |
| 9 | 1782.39 | 17.5 | 14.4 | 1.33 | 1.21 | 87.24 | 965.85 | 0.099 |
| 10 | 1980.43 | 17.7 | 13.7 | 1.31 | 1.29 | 93.47 | 981.43 | 0.105 |
| 11 | 2376.51 | 20.1 | 15.1 | 1.47 | 1.33 | 124.63 | 1043.74 | 0.136 |
| 12 | 2772.60 | 21.3 | 15.9 | 1.55 | 1.34 | 140.21 | 1074.90 | 0.150 |
| 13 | 2970.64 | 22.7 | 16.9 | 1.65 | 1.35 | 155.78 | 1090.48 | 0.167 |
| 14 | 3168.69 | 24.2 | 17.1 | 1.72 | 1.42 | 171.36 | 1121.63 | 0.180 |
| 15 | 3366.73 | 25.3 | 17.7 | 1.79 | 1.43 | 202.52 | 1279.75 | 0.188 |
| 16 | 3564.77 | 25.8 | 17.9 | 1.82 | 1.44 | 249.25 | 1495.50 | 0.200 |
| 17 | 3762.81 | 27.4 | 18.9 | 1.93 | 1.45 | 264.83 | 1468.60 | 0.220 |
| 18 | 3960.86 | 28.1 | 19.4 | 1.98 | 1.45 | 280.41 | 1515.70 | 0.227 |
| 19 | 4013.20 | 28.8 | 19.7 | 2.02 | 1.46 | 290.13 | 1546.10 | 0.231 |
| 20 | 4379.65 | 30.1 | 20.5 | 2.11 | 1.47 | 301.27 | 1556.56 | 0.240 |

Run No. 56: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 311.564 | 0.053 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 654.29 | 0.050 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1028.16 | 0.065 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1246.27 | 0.067 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1402.05 | 0.084 |
| 6 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1542.26 | 0.076 |
| 7 | 1980.43 | 13.2 | 12.5 | 1.07 | 1.06 | 124.63 | 1879.98 | 0.071 |
| 8 | 2178.47 | 14.6 | 13.0 | 1.15 | 1.12 | 124.63 | 1786.36 | 0.075 |
| 9 | 2376.51 | 15.5 | 13.3 | 1.20 | 1.17 | 140.21 | 1789.74 | 0.085 |
| 10 | 2772.60 | 17.9 | 14.2 | 1.34 | 1.26 | 155.78 | 1713.58 | 0.100 |
| 11 | 3168.69 | 19.8 | 15.2 | 1.46 | 1.30 | 186.94 | 1812.51 | 0.115 |
| 12 | 3564.77 | 21.4 | 15.6 | 1.54 | 1.37 | 218.10 | 1882.99 | 0.131 |
| 13 | 3960.86 | 22.8 | 16.3 | 1.63 | 1.40 | 311.57 | 2347.98 | 0.153 |
| 14 | 4013.20 | 23.2 | 16.4 | 1.65 | 1.41 | 373.88 | 2786.01 | 0.155 |
| 15 | 4379.65 | 24.3 | 16.8 | 1.71 | 1.45 | 482.93 | 3165.87 | 0.180 |
| 16 | 4746.10 | 26.1 | 17.6 | 1.82 | 1.48 | 638.71 | 3914.15 | 0.195 |

Run No. 57: $M_3\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $19.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 280.41 | 0.059 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 669.87 | 0.049 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1043.74 | 0.064 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1511.10 | 0.066 |
| 5 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1884.98 | 0.090 |
| 6 | 2376.51 | 13.5 | 12.5 | 1.08 | 1.08 | 178.37 | 2036.39 | 0.096 |
| 7 | 2574.56 | 15.4 | 13.2 | 1.19 | 1.17 | 186.94 | 2001.89 | 0.103 |
| 8 | 2772.60 | 16.7 | 13.8 | 1.27 | 1.21 | 202.52 | 2077.71 | 0.108 |
| 9 | 3168.69 | 19.2 | 14.6 | 1.41 | 1.31 | 233.67 | 2197.28 | 0.119 |
| 10 | 3564.77 | 21.0 | 15.7 | 1.53 | 1.34 | 264.83 | 2226.53 | 0.135 |
| 11 | 3960.86 | 21.9 | 15.8 | 1.57 | 1.39 | 311.57 | 2402.64 | 0.149 |
| 12 | 4013.20 | 22.6 | 16.0 | 1.61 | 1.41 | 373.88 | 2786.01 | 0.155 |
| 13 | 4379.65 | 24.8 | 17.2 | 1.75 | 1.44 | 436.19 | 3002.01 | 0.170 |
| 14 | 4746.10 | 27.2 | 18.6 | 1.91 | 1.46 | 560.82 | 3625.41 | 0.183 |
| 15 | 5112.55 | 29.3 | 19.9 | 2.05 | 1.47 | 577.21 | 3537.26 | 0.195 |
| 15 | 5479.00 | 31.6 | 21.2 | 2.20 | 1.49 | 623.13 | 3633.42 | 0.207 |

Run No. 58: $M_4\backslash D_4\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $19.5^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 46.740 | 825.65 | 0.060 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 1308.57 | 0.091 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 171.36 | 1916.12 | 0.098 |
| 4 | 1980.43 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 2461.38 | 0.090 |
| 5 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2663.88 | 0.089 |
| 6 | 2376.51 | 12.0 | 12.0 | 1.00 | 1.00 | 218.10 | 2663.88 | 0.089 |
| 7 | 2772.60 | 14.0 | 12.7 | 1.11 | 1.10 | 249.25 | 2792.62 | 0.098 |
| 8 | 3168.69 | 17.7 | 14.2 | 1.33 | 1.25 | 280.41 | 2784.07 | 0.112 |
| 9 | 3564.77 | 20.3 | 15.4 | 1.49 | 1.32 | 295.99 | 2825.82 | 0.117 |
| 10 | 3762.81 | 21.0 | 15.5 | 1.52 | 1.35 | 311.57 | 2886.53 | 0.121 |
| 11 | 3960.86 | 21.2 | 15.5 | 1.53 | 1.37 | 311.57 | 2671.95 | 0.132 |
| 12 | 4013.20 | 22.1 | 15.8 | 1.58 | 1.40 | 327.14 | 2750.40 | 0.135 |
| 13 | 4379.65 | 24.9 | 17.6 | 1.77 | 1.42 | 389.46 | 3038.85 | 0.147 |
| 14 | 4746.1 | 26.8 | 18.6 | 1.89 | 1.44 | 435.10 | 3188.90 | 0.158 |
| 15 | 5112.55 | 29.2 | 19.8 | 2.04 | 1.47 | 470.15 | 3219.57 | 0.171 |

Run No. 59: $M_2\backslash D_1\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 124.63 | 436.19 | 0.400 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 327.14 | 685.44 | 0.913 |
| 3 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 545.24 | 1230.68 | 0.800 |
| 4 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 887.96 | 1557.83 | 1.326 |
| 5 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 1168.37 | 2087.49 | 1.271 |
| 6 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 1557.83 | 2772.93 | 1.282 |
| 7 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 1962.86 | 3302.60 | 1.465 |
| 8 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 2445.79 | 3645.32 | 2.039 |
| 9 | 1980.43 | 13.0 | 12.2 | 1.05 | 1.06 | 2913.14 | 4112.67 | 2.429 |
| 10 | 2178.47 | 14.2 | 12.9 | 1.13 | 1.10 | 3473.96 | 4735.80 | 2.753 |
| 11 | 2376.51 | 15.0 | 13.4 | 1.18 | 1.12 | 4050.35 | 5358.93 | 3.095 |
| 12 | 2574.56 | 15.6 | 13.2 | 1.20 | 1.18 | 4813.68 | 6231.31 | 3.396 |
| 13 | 2772.60 | 17.1 | 13.9 | 1.29 | 1.23 | 5561.45 | 7166.01 | 3.466 |
| 14 | 2970.64 | 16.3 | 13.0 | 1.22 | 1.25 | 6371.52 | 7944.92 | 4.050 |
| 15 | 3168.69 | 17.1 | 13.6 | 1.28 | 1.26 | 6994.65 | 8879.62 | 3.711 |
| 16 | 3366.73 | 18.5 | 14.6 | 1.38 | 1.27 | 7835.88 | 9720.85 | 4.157 |
| 17 | 3564.77 | 19.9 | 15.6 | 1.48 | 1.28 | 8895.20 | 10655.50 | 5.053 |

Run No. 60: $M_2\backslash D_2\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 15.58 | 311.56 | 0.053 |
| 2 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 716.60 | 0.150 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 186.94 | 1183.95 | 0.188 |
| 4 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 249.25 | 1402.04 | 0.216 |
| 5 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 327.14 | 1666.88 | 0.244 |
| 6 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 405.04 | 1713.61 | 0.310 |
| 7 | 1980.43 | 13.1 | 12.3 | 1.06 | 1.06 | 467.35 | 1665.68 | 0.390 |
| 8 | 2178.47 | 13.9 | 12.7 | 1.11 | 1.09 | 545.24 | 1784.42 | 0.440 |
| 9 | 2376.51 | 14.6 | 13.0 | 1.15 | 1.12 | 623.13 | 1921.32 | 0.480 |
| 10 | 2574.56 | 15.7 | 13.3 | 1.21 | 1.18 | 716.60 | 2068.68 | 0.530 |
| 11 | 2772.60 | 16.6 | 13.4 | 1.25 | 1.24 | 825.65 | 2261.56 | 0.575 |
| 12 | 3168.68 | 18.2 | 14.2 | 1.35 | 1.28 | 1074.90 | 2554.84 | 0.726 |
| 13 | 3366.73 | 19.2 | 14.6 | 1.41 | 1.31 | 1246.26 | 2741.78 | 0.833 |
| 14 | 3564.77 | 19.8 | 15.0 | 1.45 | 1.32 | 1402.05 | 2897.56 | 0.938 |
| 15 | 3762.81 | 20.4 | 15.3 | 1.49 | 1.33 | 1370.89 | 2640.23 | 1.080 |
| 16 | 3960.86 | 20.8 | 15.5 | 1.51 | 1.34 | 1666.88 | 3116.34 | 1.150 |
| 17 | 4013.20 | 21.4 | 15.8 | 1.55 | 1.35 | 2025.18 | 3583.00 | 1.300 |
| 18 | 4379.65 | 22.3 | 16.3 | 1.61 | 1.37 | 2554.84 | 4161.66 | 1.590 |
| 19 | 4746.10 | 23.6 | 17.0 | 1.69 | 1.39 | 3271.44 | 5130.21 | 1.760 |

Run No. 61: $M_2\backslash D_3\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 701.02 | 0.098 |
| 2 | 990.21 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 841.23 | 0.125 |
| 3 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 124.63 | 1090.48 | 0.129 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 155.78 | 1495.51 | 0.116 |
| 5 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 171.36 | 1464.36 | 0.133 |
| 6 | 1980.43 | 13.1 | 12.3 | 1.06 | 1.06 | 186.94 | 1495.51 | 0.143 |
| 7 | 2178.47 | 14.6 | 13.0 | 1.15 | 1.13 | 218.10 | 1557.83 | 0.163 |
| 8 | 2376.51 | 15.9 | 13.6 | 1.23 | 1.17 | 249.25 | 1651.30 | 0.178 |
| 9 | 2772.60 | 17.1 | 13.6 | 1.28 | 1.26 | 311.57 | 1727.80 | 0.220 |
| 10 | 3168.69 | 19.1 | 14.8 | 1.41 | 1.29 | 436.19 | 1994.02 | 0.280 |
| 11 | 3366.73 | 20.1 | 15.1 | 1.47 | 1.33 | 482.93 | 2025.18 | 0.313 |
| 12 | 3564.77 | 20.8 | 15.4 | 1.51 | 1.35 | 529.66 | 2087.49 | 0.340 |
| 13 | 3762.81 | 21.3 | 15.7 | 1.54 | 1.36 | 591.98 | 2149.80 | 0.380 |
| 14 | 3960.86 | 22.1 | 16.1 | 1.59 | 1.37 | 623.13 | 2212.12 | 0.392 |
| 15 | 4013.20 | 23.0 | 16.6 | 1.65 | 1.38 | 810.07 | 2711.64 | 0.426 |
| 16 | 4379.65 | 23.7 | 16.9 | 1.69 | 1.40 | 965.85 | 2978.04 | 0.480 |
| 17 | 4746.10 | 25.2 | 17.8 | 1.79 | 1.42 | 1339.73 | 3966.65 | 0.510 |
| 18 | 5112.55 | 25.7 | 18.0 | 1.82 | 1.43 | 1713.61 | 4773.63 | 0.560 |

Run No. 62: $M_2\backslash D_5\backslash d_{p4}\backslash h_{s2}\backslash P_{12}$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 50.63 | 739.97 | 0.073 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1074.89 | 0.053 |
| 3 | 1386.30 | 12.0 | 12.0 | 1.00 | 1.00 | 54.52 | 1208.87 | 0.047 |
| 4 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 58.42 | 1409.84 | 0.043 |
| 5 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1433.19 | 0.045 |
| 6 | 1980.43 | 13.5 | 12.5 | 1.08 | 1.08 | 62.31 | 1665.76 | 0.039 |
| 7 | 2178.47 | 14.6 | 13.0 | 1.15 | 1.12 | 66.21 | 1699.79 | 0.041 |
| 8 | 2376.51 | 16.0 | 13.3 | 1.22 | 1.20 | 77.89 | 1736.93 | 0.047 |
| 9 | 2772.60 | 18.6 | 14.2 | 1.37 | 1.31 | 85.68 | 1774.15 | 0.051 |
| 10 | 3168.69 | 21.1 | 15.9 | 1.54 | 1.33 | 109.05 | 1896.72 | 0.061 |
| 11 | 3564.77 | 23.1 | 17.0 | 1.67 | 1.36 | 112.94 | 1824.17 | 0.066 |
| 12 | 3762.81 | 24.5 | 17.3 | 1.74 | 1.42 | 128.52 | 1871.73 | 0.074 |
| 13 | 3960.86 | 25.6 | 17.8 | 1.81 | 1.44 | 140.20 | 1914.95 | 0.079 |
| 14 | 4013.20 | 26.1 | 17.9 | 1.83 | 1.46 | 179.15 | 2134.79 | 0.092 |
| 15 | 4379.65 | 27.6 | 18.3 | 1.91 | 1.51 | 225.00 | 2242.83 | 0.112 |
| 16 | 4746.10 | 30.1 | 19.4 | 2.06 | 1.55 | 255.37 | 2314.84 | 0.124 |
| 17 | 5112.55 | 31.1 | 19.6 | 2.11 | 1.59 | 278.86 | 2386.62 | 0.132 |
| 18 | 5479 | 31.9 | 19.7 | 2.15 | 1.62 | 302.22 | 2460.08 | 0.140 |

Run No. 63: $M_2\backslash D_4\backslash d_{p1}\backslash h_{s2}\backslash P_{12}$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 872.39 | 0.057 |
| 2 | 514.91 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1246.27 | 0.067 |
| 3 | 712.95 | 14.3 | 13.0 | 1.14 | 1.10 | 93.47 | 2125.43 | 0.052 |
| 4 | 792.17 | 15.1 | 13.2 | 1.18 | 1.15 | 93.47 | 1890.97 | 0.057 |
| 5 | 990.21 | 16.2 | 13.6 | 1.24 | 1.19 | 93.47 | 1733.29 | 0.062 |
| 6 | 1188.26 | 16.7 | 13.6 | 1.26 | 1.23 | 93.47 | 1601.05 | 0.066 |
| 7 | 1386.30 | 17.1 | 13.7 | 1.28 | 1.25 | 93.47 | 1509.68 | 0.076 |
| 8 | 1584.34 | 18.3 | 14.1 | 1.35 | 1.30 | 109.05 | 1543.92 | 0.085 |
| 9 | 1980.43 | 19.7 | 15.1 | 1.45 | 1.31 | 109.05 | 1391.99 | 0.110 |
| 10 | 2376.51 | 21.6 | 16.1 | 1.57 | 1.34 | 140.21 | 1414.85 | 0.142 |
| 11 | 2772.60 | 23.0 | 16.9 | 1.66 | 1.36 | 171.36 | 1378.12 | 0.160 |
| 12 | 3564.77 | 25.8 | 18.4 | 1.84 | 1.40 | 202.52 | 1359.78 | 0.192 |
| 13 | 3960.86 | 26.5 | 18.8 | 1.89 | 1.41 | 264.83 | 1644.15 | 0.271 |
| 14 | 4379.65 | 28.6 | 18.9 | 1.98 | 1.51 | 389.46 | 1650.65 | 0.342 |

Run No. 64: $M_2\backslash D_4\backslash d_{p2}\backslash h_{s2}\backslash P_{12}$ Temperature $21.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 475.30 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 856.81 | 0.078 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 62.31 | 1168.37 | 0.056 |
| 3 | 712.95 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 1261.84 | 0.066 |
| 4 | 792.17 | 13 | 12.2 | 1.05 | 1.06 | 93.47 | 1926.22 | 0.051 |
| 5 | 911.00 | 13.7 | 12.7 | 1.10 | 1.08 | 93.47 | 1625.77 | 0.061 |
| 6 | 990.21 | 14.3 | 12.9 | 1.13 | 1.11 | 109.05 | 1812.96 | 0.064 |
| 7 | 1109.04 | 15.3 | 13.5 | 1.20 | 1.14 | 109.05 | 1736.66 | 0.067 |
| 8 | 1188.26 | 16.4 | 13.4 | 1.24 | 1.22 | 109.05 | 1644.97 | 0.071 |
| 9 | 1386.30 | 15.7 | 12.6 | 1.18 | 1.25 | 109.05 | 1563.05 | 0.075 |
| 10 | 1584.34 | 17.1 | 13.4 | 1.27 | 1.27 | 124.63 | 1663.27 | 0.081 |
| 11 | 1782.39 | 18.5 | 14.4 | 1.37 | 1.29 | 130.86 | 1635.00 | 0.087 |
| 12 | 1980.43 | 19.8 | 15.0 | 1.45 | 1.32 | 140.21 | 1616.11 | 0.095 |
| 13 | 2376.51 | 21.4 | 16.0 | 1.56 | 1.34 | 155.78 | 1510.39 | 0.115 |
| 14 | 2772.60 | 22.3 | 16.3 | 1.61 | 1.37 | 155.78 | 1666.88 | 0.103 |
| 15 | 3168.69 | 24.8 | 17.9 | 1.78 | 1.39 | 218.10 | 1729.19 | 0.144 |
| 16 | 3564.77 | 25.6 | 18.1 | 1.82 | 1.41 | 311.57 | 1791.50 | 0.211 |
| 17 | 3960.86 | 26.7 | 18.7 | 1.89 | 1.43 | 358.30 | 1822.66 | 0.245 |
| 18 | 4013.20 | 27.2 | 18.9 | 1.92 | 1.44 | 405.04 | 1884.97 | 0.274 |
| 19 | 4379.65 | 27.7 | 19.1 | 1.95 | 1.45 | 436.19 | 1978.44 | 0.283 |

Run No. 65: $M_2\backslash D_4\backslash d_{p3}\backslash h_{s2}\backslash P_{12}$ Temperature $22.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 591.97 | 0.056 |
| 2 | 594.13 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 950.28 | 0.089 |
| 3 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 93.47 | 1324.15 | 0.076 |
| 4 | 990.21 | 12.7 | 12.2 | 1.04 | 1.04 | 109.05 | 1926.55 | 0.060 |
| 5 | 1188.26 | 14.5 | 13.1 | 1.15 | 1.11 | 109.05 | 1712.73 | 0.068 |
| 6 | 1386.30 | 16.1 | 13.7 | 1.24 | 1.18 | 109.05 | 1563.05 | 0.075 |
| 7 | 1584.34 | 17.5 | 13.9 | 1.31 | 1.26 | 109.05 | 1507.13 | 0.078 |
| 8 | 1782.39 | 17.9 | 14.0 | 1.33 | 1.28 | 124.63 | 1573.82 | 0.086 |
| 9 | 1980.43 | 18.8 | 14.3 | 1.38 | 1.31 | 124.63 | 1479.30 | 0.092 |
| 10 | 2376.51 | 20.9 | 15.3 | 1.51 | 1.37 | 155.78 | 1571.96 | 0.110 |
| 11 | 2772.60 | 22.7 | 16.1 | 1.62 | 1.41 | 171.36 | 1553.30 | 0.124 |
| 12 | 2970.64 | 23.6 | 16.7 | 1.68 | 1.41 | 186.94 | 1582.02 | 0.134 |
| 13 | 3168.69 | 24.6 | 17.4 | 1.75 | 1.41 | 202.52 | 1597.60 | 0.129 |
| 14 | 3564.77 | 25.7 | 18.0 | 1.82 | 1.43 | 264.83 | 1659.91 | 0.167 |
| 15 | 3762.81 | 26.3 | 18.1 | 1.85 | 1.45 | 295.99 | 1691.07 | 0.190 |
| 16 | 3960.86 | 26.1 | 17.9 | 1.83 | 1.46 | 327.14 | 1722.22 | 0.214 |
| 17 | 4013.20 | 26.8 | 17.6 | 1.85 | 1.52 | 389.46 | 1784.54 | 0.245 |

Run No. 66: $M_2\backslash D_4\backslash d_{p5}\backslash h_{s2}\backslash P_{12}$ Temperature $20.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 12.0 | 12.0 | 1.00 | 1.00 | 31.16 | 295.98 | 0.105 |
| 2 | 1188.26 | 12.0 | 12.0 | 1.00 | 1.00 | 46.74 | 498.50 | 0.094 |
| 3 | 1584.34 | 12.0 | 12.0 | 1.00 | 1.00 | 77.89 | 745.33 | 0.105 |
| 4 | 1782.39 | 12.0 | 12.0 | 1.00 | 1.00 | 109.05 | 945.74 | 0.115 |
| 5 | 2178.47 | 12.0 | 12.0 | 1.00 | 1.00 | 140.21 | 1167.48 | 0.120 |
| 6 | 2574.56 | 12.0 | 12.0 | 1.00 | 1.00 | 193.17 | 1536.46 | 0.126 |
| 7 | 2772.60 | 12.0 | 12.0 | 1.00 | 1.00 | 202.52 | 1755.26 | 0.115 |
| 8 | 2970.64 | 13.0 | 12.4 | 1.06 | 1.05 | 218.10 | 2155.47 | 0.101 |
| 9 | 3168.69 | 14.1 | 12.8 | 1.12 | 1.10 | 249.25 | 2208.83 | 0.113 |
| 10 | 3564.77 | 15.6 | 13.2 | 1.20 | 1.18 | 295.99 | 2242.55 | 0.132 |
| 11 | 3960.86 | 17.9 | 13.8 | 1.32 | 1.30 | 342.72 | 2377.63 | 0.144 |
| 12 | 4013.20 | 19.1 | 14.5 | 1.40 | 1.31 | 375.27 | 2421.16 | 0.155 |
| 13 | 4379.65 | 20.8 | 15.4 | 1.51 | 1.35 | 402.55 | 2476.57 | 0.163 |
| 14 | 4746.10 | 21.6 | 15.6 | 1.55 | 1.39 | 452.48 | 2544.81 | 0.178 |

Run No. 67: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s1}\backslash P_{12}$ Temperature $19.0^0C$

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 8.0 | 8.0 | 1.00 | 1.00 | 46.74 | 482.93 | 0.107 |
| 2 | 990.21 | 8.0 | 8.0 | 1.00 | 1.00 | 62.31 | 607.56 | 0.114 |
| 3 | 1188.26 | 8.0 | 8.0 | 1.00 | 1.00 | 77.89 | 732.18 | 0.119 |
| 4 | 1386.30 | 8.0 | 8.0 | 1.00 | 1.00 | 93.47 | 872.39 | 0.120 |
| 5 | 1584.34 | 8.0 | 8.0 | 1.00 | 1.00 | 124.63 | 1012.59 | 0.140 |
| 6 | 1782.39 | 8.0 | 8.0 | 1.00 | 1.00 | 124.63 | 1012.59 | 0.140 |
| 7 | 1980.43 | 9.1 | 8.4 | 1.09 | 1.08 | 124.63 | 1129.71 | 0.124 |
| 8 | 2178.47 | 10.1 | 8.8 | 1.18 | 1.15 | 130.86 | 1129.79 | 0.131 |
| 9 | 2376.51 | 11.0 | 9.2 | 1.26 | 1.20 | 140.21 | 1120.70 | 0.143 |
| 10 | 2772.60 | 12.0 | 9.7 | 1.36 | 1.24 | 155.78 | 1160.81 | 0.155 |
| 11 | 2970.64 | 12.8 | 10.2 | 1.44 | 1.25 | 171.36 | 1191.36 | 0.168 |
| 12 | 3168.69 | 13.6 | 10.7 | 1.52 | 1.27 | 186.94 | 1215.11 | 0.182 |
| 13 | 3366.73 | 14.3 | 11.0 | 1.58 | 1.30 | 218.10 | 1246.26 | 0.212 |
| 14 | 3564.77 | 15.8 | 12.0 | 1.74 | 1.32 | 249.25 | 1382.20 | 0.220 |
| 15 | 3960.86 | 17.2 | 12.7 | 1.87 | 1.36 | 280.41 | 1448.79 | 0.240 |
| 16 | 4013.20 | 17.8 | 12.8 | 1.91 | 1.39 | 358.30 | 1752.46 | 0.257 |
| 17 | 4379.65 | 18.2 | 12.7 | 1.93 | 1.43 | 451.77 | 2118.82 | 0.271 |
| 18 | 4746.10 | 19.6 | 11.6 | 1.95 | 1.68 | 654.29 | 2910.46 | 0.290 |

Run No. 68: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s3}\backslash P_{12}$ Temperature 21.0$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 792.17 | 16.0 | 16.0 | 1.00 | 1.00 | 46.74 | 887.96 | 0.056 |
| 2 | 1188.26 | 16.0 | 16.0 | 1.00 | 1.00 | 85.68 | 1386.46 | 0.066 |
| 3 | 1584.34 | 16.0 | 16.0 | 1.00 | 1.00 | 109.05 | 1947.29 | 0.059 |
| 4 | 1782.39 | 16.0 | 16.0 | 1.00 | 1.00 | 124.63 | 2071.91 | 0.064 |
| 5 | 1980.43 | 17.1 | 16.5 | 1.05 | 1.04 | 140.21 | 1931.71 | 0.078 |
| 6 | 2178.47 | 18.6 | 16.9 | 1.11 | 1.10 | 140.21 | 2009.60 | 0.075 |
| 7 | 2376.51 | 20.9 | 17.8 | 1.21 | 1.17 | 140.21 | 1915.02 | 0.079 |
| 8 | 2772.60 | 21.7 | 18.3 | 1.25 | 1.19 | 171.36 | 2165.38 | 0.086 |
| 9 | 2970.64 | 23.5 | 19.4 | 1.34 | 1.21 | 177.59 | 2165.39 | 0.089 |
| 10 | 3168.69 | 24.4 | 20.0 | 1.39 | 1.22 | 186.94 | 2196.53 | 0.093 |
| 11 | 3366.73 | 25.5 | 20.9 | 1.45 | 1.22 | 202.52 | 2258.85 | 0.099 |
| 12 | 3564.77 | 26.7 | 21.6 | 1.51 | 1.24 | 233.67 | 2438.10 | 0.106 |
| 13 | 3762.81 | 27.9 | 22.0 | 1.56 | 1.27 | 249.25 | 2435.65 | 0.114 |
| 14 | 3960.86 | 29.2 | 22.3 | 1.61 | 1.31 | 264.83 | 2490.29 | 0.119 |
| 15 | 4013.20 | 29.9 | 22.3 | 1.63 | 1.34 | 273.04 | 2511.05 | 0.122 |
| 16 | 4379.65 | 32.1 | 22.6 | 1.71 | 1.42 | 301.05 | 2634.78 | 0.129 |
| 17 | 4746.10 | 34.1 | 23.2 | 1.79 | 1.47 | 329.34 | 2787.13 | 0.134 |
| 18 | 5479.00 | 36.3 | 23.9 | 1.88 | 1.52 | 386.69 | 2999.44 | 0.148 |

Run No. 69: $M_2\backslash D_4\backslash d_{p4}\backslash h_{s4}\backslash P_{12}$ Temperature 19.0$^0$C

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|
| 1 | 396.09 | 20.0 | 20.0 | 1.00 | 1.00 | 31.16 | 482.92 | 0.069 |
| 2 | 792.17 | 20.0 | 20.0 | 1.00 | 1.00 | 46.74 | 1090.49 | 0.045 |
| 3 | 1188.26 | 20.0 | 20.0 | 1.00 | 1.00 | 77.89 | 1729.19 | 0.047 |
| 4 | 1386.30 | 20.0 | 20.0 | 1.00 | 1.00 | 109.05 | 2103.05 | 0.055 |
| 5 | 1584.34 | 20.0 | 20.0 | 1.00 | 1.00 | 124.63 | 2352.31 | 0.056 |
| 6 | 1782.39 | 20.0 | 20.0 | 1.00 | 1.00 | 124.63 | 2632.73 | 0.050 |
| 7 | 1980.43 | 21.8 | 20.6 | 1.06 | 1.06 | 140.21 | 2736.69 | 0.054 |
| 8 | 2178.47 | 22.8 | 21.2 | 1.10 | 1.08 | 140.21 | 2461.38 | 0.060 |
| 9 | 2376.51 | 24.5 | 22.3 | 1.17 | 1.10 | 140.21 | 2539.26 | 0.058 |
| 10 | 2772.60 | 27.2 | 24.0 | 1.28 | 1.13 | 171.36 | 2757.34 | 0.066 |
| 11 | 3168.69 | 28.0 | 24.8 | 1.32 | 1.13 | 202.52 | 2976.77 | 0.073 |
| 12 | 3366.73 | 30.0 | 25.2 | 1.38 | 1.19 | 233.67 | 3191.52 | 0.079 |
| 13 | 3564.77 | 32.2 | 25.8 | 1.45 | 1.25 | 249.25 | 3288.88 | 0.082 |
| 14 | 3762.81 | 33.2 | 26.4 | 1.49 | 1.26 | 264.83 | 3274.26 | 0.088 |
| 15 | 3960.86 | 34.1 | 27.1 | 1.53 | 1.26 | 295.99 | 3548.63 | 0.091 |
| 16 | 4379.65 | 36.3 | 28.5 | 1.62 | 1.27 | 324.55 | 3636.28 | 0.098 |
| 17 | 5112.55 | 39.6 | 30.0 | 1.74 | 1.32 | 357.31 | 3728.16 | 0.106 |

# APPENDIX 2

(Terminal velocity of different materials and sizes)

| Material | Particle size ($d_p$),mm | Terminal velocity ($G_t$), kg/hr-m$^2$ |
|---|---|---|
| Dolomite | 1.125 | 26914 |
| Dolomite | 0.725 | 23002 |
| Dolomite | 0.4625 | 18243 |
| Dolomite | 0.390 | 16489 |
| Dolomite | 0.3275 | 14645 |
| Alum | 0.725 | 16195 |
| Fe-Ore | 0.725 | 25717 |
| Mn-Ore | 0.725 | 30028 |

# APPENDIX 3

## (LIST OF PUBLICATIONS)

A. Directly based on Ph. D. work

| Sl. No. | Title of the paper | Journal/Proceeding |
|---|---|---|
| 1 | Effect of different types of promoters on bed expansion in a gas-solid fluidized bed with varying distributor open areas. | Journal of Chemical Engineering of Japan, 35 (7) (2002) 681 |
| 2 | Effect of co-axial rod, disk and blade type promoters on bed fluctuation in a gas-solid fluidized bed with varying distributor open area. | Journal of the Institution of Engineers (India), 82 (2002) 61. |
| 3 | Minimum fluidization velocity in gas-solid fluidized beds with co-axial rod and disk promoters | Indian Chemical Engineer, 44 (4) (2002) 256 |
| 4 | Fluidized bed pressure drop in promoted gas-solid beds with co-axial rod, disk and blade type promoters. | Chemical Engineering Communications (in press) |
| 5 | Pressure drop ratio in promoted gas-solid fluidized beds. | Communicated to Journal of Hydraulic Research. |
| 6 | Bubble behaviour in gas-solid fluidized beds with co-axial rod, disk and blade type promoters | Communicated to Journal of the Institution of Engineers (India). |
| 7 | Artificial neural network based estimation of bed expansion in gas-solid fluidized beds. | Indian Chemical Engineering Congress (2002) 135 |
| 8 | Prediction of minimum fluidization velocity in a promoted gas-solid fluidized bed. | Indian Chemical Engineering Congress (2000) TP 51-54. |
| 9 | Prediction of bed expansion and bed fluctuation in a promoted gas-solid fluidized bed with distributors of varying open area. | Indian Chemical Engineering Congress (2000) TPM 17-20. |

B. Other related work

| Sl. No. | Title of the paper | Journal/Proceeding |
|---|---|---|
| 1 | Effect of liquid viscosity on pressure drop in batch liquid-solid fluidized beds. | Journal of the Institution of Engineers (India), 83 (2002) 9. |
| 2 | Effect of co-axial rod-promoter on the pressure drop in a batch liquid-solid fluidized bed. | Journal of the Institution of Engineers (India), 79 (1998) 30. |
| 3 | Effect of fluid viscosity and promoter parameter on pressure drop in a batch liquid-solid fluidized bed with co-axial disc promoter | Journal of the Institution of Engineers (India), 80 (2000) 44. |
| 4 | Influence of coaxial-rod- and coaxial-blade-type baffles on bed expansion in gas-solid fluidization | Powder Technology, 126 (2002) 91. |

# APPENDIX 4

# Reprint of papers

**The reprint of the following papers have been included in this thesis:**

- Effect of different types of promoters on bed expansion in a gas-solid fluidized bed with varying distributor open areas – Journal of Chemical Engineering of Japan, vol. 35, No. 7 (2002) 681-686.
- Effect of co-axial rod, disk and blade type promoters on bed fluctuation in a gas-solid fluidized bed with varying distributor open areas – Journal of the Instn. Of Engrs. (India) – CH Div. , vol. 82 (2002) 61-68.
- Fluidized bed pressure drop in promoted gas-solid beds with co-axial rod, disk and blade type promoters – Chem. Engg. Commun. (in press).
- Minimum fluidization velocity in gas-solid fluidized beds with co-axial rod and disk promoters - Indian Chemical Engineer, vol. 44 (4) (2002) 256-260.
- Influence of coaxial-rod- and coaxial-blade-type baffles on bed expansion in gas-solid fluidization – Powder Technology, vol. 126 (2002) 91-95.